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10 000-Hour Cyclic Oxidation Behavior at 982 °C (1800 °F) of 68 High-Temperature Co-, Fe-, and Ni-Base Alloys

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INTRODUCTION

Power systems with operating temperatures in the range of 815 to 982 °C (1500 to 1800 °F) frequently require alloys that can operate for long times at such temperatures. A critical requirement is that these alloys have adequate oxidation (scaling) resistance. This implies the use of Fe-, Ni-, and Co-base high temperature alloys with sufficient Cr and/or Al content(s) to confer this resistance. The alloys used in these power systems will require thousands of hours of operating life with intermittent shut-downs to room temperature. Thus, alloy selection must consider long-time cyclic oxidation behavior. However, most oxidation data heretofore available for such alloys are mostly for isothermal (i.e., noncyclic conditions). As a first approximation, long-time (greater than 1000 hr) behavior can be predicted from the isothermal parabolic scaling constant k_p derived from shorter time (usually a few hundred hours) weight change versus time data (ref. 8).

Intermittent power plant shut-downs, however, offer the possibility that the protective scale will tend to spall (i.e., crack and flake-off) upon cooling, increasing the rate of oxidation attack in subsequent heating cycles. Thus, it is critical, that for alloys evaluated for oxidation resistance, a better estimate of their cyclic oxidation behavior be made. It was determined that exposing test alloys for ten-1000 hr cycles in static air at 982 °C (1800 °F) could give a reasonable simulation of long-time power plant operation. Sixty-eight Co-, Fe-, and Ni-base high temperature alloys, typical of those used at this temperature or higher, were used in this study. The alloys were evaluated and compared on the basis of the specific weight change versus time data, x-ray diffraction and appearance of the test samples after test.

MATERIALS AND PROCEDURE

Sixty-eight alloys in the Co-, Fe-, and Ni-base metal systems were tested in this study. They are listed in table I along with their nominal chemical compositions in weight percent. The alloys are grouped by base-metal and sub-grouped by the type of alloy (e.g., Ni-base heater/sheet alloys). This approach of organizing the alloys as 11 sub-groups will be continued throughout this study.

All the alloys were tested as small coupons roughly 12.7 mm wide and 19 to 32 mm long with a 32 mm diameter hanger hole. The thickness of each sample is listed in a table in appendix A. In most cases replicate samples were run.

The test samples in the as-received condition were measured, degreased, ultrasonically cleaned, and weighed to the nearest 0.1 mg. They were then suspended on individual quartz hooks attached to a quartz rod lattice two-tier rack. The lattices were placed in a box furnace held at a temperature of 982 °C (1800 °F). After 1000 hr the samples were removed, cooled to room temperature and weighed to the nearest 0.1 mg. This procedure was repeated until ten 1000-hr cycles were completed. After final weighing, the samples were photographed, the appearance noted, and finally the sample surface was analyzed by x-ray diffraction (XRD) to determine the oxides present on each alloy. Specific weight change versus time data were generated for each test sample from the sample weights and the initial sample area. This gravimetric data was the primary basis for analyzing the oxidation behavior of the alloys.

As a further aid in comparing results, the samples were ranked after test as to their general appearance, nature of the scale, tendency of the scale to spall while handling, etc. This is a subjective relative evaluation exclusive of the weight change data with a ranking of 1 (excellent), to 5 (catastrophic). Both the XRD and scale ranking criteria will be used below along with the specific weight change data in a final overall cyclic oxidation evaluation of each alloy.

RESULTS

A total of 68 Co-, Fe-, and Ni-base alloys were tested representing 132 runs at 982 °C (1800 °F) in static air for ten-1000 hr exposure cycles. The specific weight change versus time data generated was used to infer oxidation kinetics. Some typical specific weight change versus time data (i.e., $\Delta W/A$ versus t) are shown in figures 1 to 9. These plots represent a range of oxidation behavior including parabolic, paralinear, linear and mixed linear kinetics. The gravimetric/time data was fitted to the basic paralinear equation:

(1) $\Delta W/A = k_1^{1/2} t^{1/2} + k_2 t \pm \text{S.E.E.}$ by multiple linear regression.

The use of this equation is discussed in detail in appendix A where depending upon the degree of fit, the significance and sign of the constants $k_1^{1/2}$ and k_2 define the kinetic model and S.E.E. is the standard error at estimate. Figures 1 to 9 show both the observed data values (the circles) and the derived data values (the squares) indicate the degree of fit to the various models. Of the 132 runs, 94 were classified by regression results as paralinear (model 1), 4 were parabolic (model 2), while 34 were linear or mixed-linear (model 3). If only the $k_1^{1/2}$ term[1] is significant this implies parabolic kinetics where scale growth is the only controlling factor. In paralinear oxidation both the scale growth constant, $k_1^{1/2}$ and the scale loss constant, usually through spalling $-k_2$ are significant. In the linear case massive scale growth or loss usually overwhelms the basic model equation (1) forcing simple linear kinetics.

In theory, straight parabolic oxidation is preferred in cyclic oxidation tests indicating no difference between cyclic and isothermal response at elevated temperatures. However, in practice, an alloy with a low scale growth rate coupled with a low scale loss[2] (i.e., paralinear behavior) is usually favored over an alloy with a much higher growth rate and no significant scale loss (i.e., parabolic behavior). For example, compare Ni-270, which displays parabolic growth of predominately NiO scale, with a paralinear Cr_2O_3 protective scale forming alloy like Tophet 30. Here the Ni-270 has an oxidation ranking of poor while that of Tophet 30 is good. Linear kinetics, on the other hand, usually results from massive growth and/or scale loss rates leading to catastrophic oxidation behavior.

The regression coefficient(s) for the various kinetic models can be combined into a single oxidation attack parameter, here defined as KB3. This parameter derivation is outlined in appendix A and is one of three factors along with an appearance description ranking and the x-ray diffraction data to analyze the cyclic oxidation behavior

The post-test appearance description data for each alloy is described in table II and each alloy is ranked as follows:

1 Excellent
2 Good
3 Fair
4 Poor
5 Catastrophic

The x-ray diffraction (XRD) results are summarized in table III. The alloys are grouped as before and the phases are listed in descending order of intensity. It is assumed in most cases that the strongest x-ray intensity phase is most abundant. The alloys in the main can be divided into two basic groups as discussed previously (refs. 2, 5, 7 to 9). As is expected for most of the high-Cr alloys chromia (Cr_2O_3) and chromite spinels [(Co, Fe, and Ni) Cr_2O_4] with a_o's ranging from 8.30 to 8.45 Å are most abundant. Other alloys with significant Al and normally a minimum Cr content tend to form alumina (Al_2O_3) and aluminate spinels [(Co, Fe, and Ni) Al_2O_4] with a_o's ranging from 8.10 to 8.20 Å. When these alloys ultimately fail, it is because the Cr and/or Al levels fall below a certain critical value favoring the formation of the less protective base-metal oxides of Co, Fe or Ni.

[1] Here $(k_1^{1/2})^2$ is effectively kp-the parabolic scaling constant.

[2] This scale loss term is mostly due to scale spalling between heating cycles. There may also be some at temperature spalling and/or scale vaporization. In addition this term may include a positive component, due to sample growth from cracking or "fretting" of the specimen either at temperature or upon cool-down or heat-up. These "at temperature" effects can usually be detected in a continuous weighing, isothermal oxidation test.

The attack parameter, KB3 and the visual oxidation ranking are highly correlated and can be combined into a single rating parameter, KB4 by the expression:

$$\mathrm{KB4} = \mathrm{KB3}\left[1 + 0.1(\mathrm{rank} - 1)\right] \tag{2}$$

This will tend to provide an overall oxidation rating which is a slightly more conservative estimate. This is particularly true as the oxidation resistance decreases (i.e., the higher the visual ranking).

The adjusted attack parameter, termed KB4, better reflects the actual cyclic oxidation resistance of the alloys tested. These KB4 values are listed in table IV, by alloy, in decreasing order of their oxidation resistance based on the maximum KB4 value for each alloy. Figure 10 shows four typical oxidation plots representing “excellent” to “fair” behavior. The two alloys U-700 and IN-702 ranked as “excellent” show very little specific weight change over the 10 000 hr test time. HAS-X and DH-242, ranked “good” and “fair” respectively, exhibited an increased degree of specific weight change. The various bar graphs (figs. 11 to 18) showing the replicate KB4 values for a given alloy indicate the good reproducibility of the gravimetric data.

DISCUSSION OF RESULTS

The 68 alloys tested can be divided mainly into 2 basic groups based primarily on the x-ray diffraction results and the alloy chemistry. Fifty-one of the 68 alloys tested are basically chromia/chromite spinel protective oxide formers and tend to fail when Cr is depleted and base metal scales become controlling. These include 23 of the 35 Ni-base, 20 of the 25 Fe-base, and all 8 of the Co-base alloys. These results are summarized in figures 11 to 13 where the maximum KB4 values for each alloy are plotted in order of decreasing Cr content for each alloy base. Multiple regression analysis of the KB4-Max values for each alloy system as a function of the alloy chemistry show that the oxidation resistance increases with Cr content. For the Ni-base system (fig. 13) the optimum Cr content is close to 32 percent. For good to excellent resistance, a minimum of 15 percent Cr is required. Two alloys similar in appearance and in observed oxides, but with drastically different KB4 results, were quite anomalous. HAS-S appears better than its composition would imply possibly due to the presence of 0.02 percent La which could inhibit spalling. Incoloy-804 is poorer than expected apparently due to the high Fe content. The 20 Fe-base chromia/chromite formers follow the same general trend: The higher the Cr content, the better the oxidation resistance, though not so good as the Ni-base chromia/chromite formers. None of these alloys fall into the “excellent” range, with only 4 in the “good” range: RA-26-1, RA-310, Incoloy-800, and RA-330. All the rest are poor to catastrophic. These “good” Fe-base chromia/chromite formers should not have less than 20 percent Cr.[3] It is not clear why RA-310 and 310 S.S. behave so differently. These Fe-base alloys appear similar and have comparable XRD results, but RA-310 has a much lower KB4 value in the “good” range compared to the “poor” ranking of 310 S.S. The 8 Co-base alloys are all chromia/chromite formers and the KB4-max values for each alloy are plotted on figure 11. They all have high Cr contents ranging from 28 to 20 percent. Cr Alloys with 25 to 28 percent Cr have “good” to “excellent” cyclic oxidation resistance. HA-188, with 23.5 percent Cr, also has “good” oxidation resistance probably due to 0.08 percent La additions to inhibit spalling. MAR-M-509, with 23.5 percent Cr and 7 percent W, with a “fair” ranking and WI-52, with 21 percent Cr and 11 percent W, and L-605, with 20 percent Cr and 15 percent W, with “catastrophic” and “poor” ranking, respectively, have much worse cyclic oxidation resistance due to a combination of lower Cr content and quite high W content.

Of the remaining 17 alloys, 15 can be classified as conferring cyclic oxidation resistance by forming alumina/aluminate scales. Ten alloys are Ni-base while the remaining five are Fe-base. The KB4 values versus alloy for both alloy systems are shown in figures 14 and 15, plotted with decreasing Al content for each system. The behavior of the Ni-base alumina/aluminate scale forming alloys are fairly complex in that they have a narrow range of Al content (3.1 to 6 percent), as well as a minimum Cr content of 6 percent, which is necessary to stabilize the alumina/aluminate oxide. In addition, the formation of a tri-rutile oxide, such as tapiolite-Ni $(Nb, Ta, Mo, W)_2O_6$ (e.g., refs. 1, 4, 9, 14, 16, 18) has helped increase the oxidation resistance due to the high levels of the refractory metal Ta (e.g., B-1900, TAZ-8A and NASA-VIA) and Mo for U-700. Of the 10 alumina/aluminate forming Ni-base alloys, IN-100 has a much poorer cyclic oxidation resistance than would be expected from its alloy composition. The high

[3]The chromia scale on these alloys does tend to vaporize with increasing temperature, particularly above 1100 °C. At this lower temperature it appears, at most, to be a small percentage of the negative linear rate constant, k_2 (refs. 20 to 23).

KB4 values for this alloy are not particularly consistent with its appearance, but more so with its XRD results; i.e., no strong $\propto Al_2O_3$ peaks. It was inferred in a previous investigation (refs. 6 and 9) that the 1 percent V level caused the IN-100 to behave poorly in static cyclic furnace tests.

The two remaining alloys, Ni-270 and WAZ-20 are basically NiO formers. Their KB4 values are plotted on figure 16 and fall in the "poor" and "catastrophic" range, respectively, reflecting the unprotective nature of the NiO scale. Since the nickel oxide on the Ni-270 is a nonspalling, coherent scale with close to a pure parabolic scaling rate, it falls within the range of the pure isothermal parabolic scaling constant for NiO (ref. 24). The Ni-base WAZ-20 with 6.5 percent Al and 18.5 percent W under these test conditions forms no protective alumina/aluminate scale with the W making the scaling resistance even worse than pure nickel. With this level of Al a minimal amount of Cr is required to stabilize Al_2O_3 formation.

The KB4 values are listed in ascending order of the maximum KB4 value for each alloy in table IV. Of most interest are the 16 alloys rated "excellent" with KB4 values less than 0.2. This includes 3 Co-base, 5 Fe-base, and 8 Ni-base alloys and are plotted as bar graphs in figure 17. The "best" of these are shown in figure 17 which have KB4 rating of less than 0.1. These 9 alloys show virtually no significant oxidation attack with thin coherent scales of various colors. All nine of these alloys are alumina/aluminate spinel formers.

SUMMARY OF RESULTS

Sixty-eight high temperature Co-, Fe-, and Ni-base alloys were tested for 10-one thousand hours in static air at 982 °C (1800 °F). The oxidation behavior of the samples was evaluated by specific weight change, x-ray diffraction, and final appearance of the samples. The gravimetric and appearance data were combined into a modified oxidation attack parameter, KB4 to rank the alloys on a relative basis using a single rating factor. The results can be summarized as follows:

1. The specific weight change versus time data can be fit to the quasi-paralinear equation: $\Delta W/A = k_1^{1/2}t^{1/2} + k_2t \pm$ S.E.E. where $k_1^{1/2}$ represents a scale growth constant and k_2 either when negative a spalling constant or when positive a linear growth constant and S.E.E. is the standard error of estimate. These two constants can be combined into a single constant here defined as a single attack parameter, KB3 for these long cycle time, long time tests. This KB3 parameter was further modified by a descriptive numerical ranking to rate all the alloys on a quantitative scale to classify the oxidation resistance from excellent to catastrophic.
2. Based on alloy chemistry and x-ray diffraction results, the alloys fall into three classes depending on the rate controlling oxide scales formed.

   Class I: Cr_2O_3/chromite spinel control - 51 of 68 alloys tested including 8 Co-base, 20-Fe-base, and 23 Ni-base.
   Class II: $\propto Al_2O_3$/aluminate spinel control - 15 of 68 alloys tested including 5-Fe-base, and 10 Ni-base.
   Class III: NiO control - 2 of 68 alloys tested including 2 Ni-base.

3. Cr_2O_3/chromite spinel control depends mainly on the Cr content in a given alloy. To form and maintain a protective oxide roughly at least 16 percent Cr is necessary with the optimum approaching 30 percent Cr regardless of the alloy base. In general in this type of scale formation, Co-base alloys are superior to Ni-base which in turn are much superior to Fe-base.
4. It was surprising that the commercial Fe-base chromia forming stainless steels whether ferritic (e.g., 410 S.S., 430 S.S.) or austenitic (e.g., 304 S.S., 316 S.S.) showed such poor cyclic oxidation resistance under these test conditions even through most of them, particularly the 300 S.S. series, had quite high Cr contents.
5. $\propto Al_2O_3$/aluminate spinel control requires at least 3.1 to 6.0 percent Al and a minimum of 6 percent Cr content in Ni-base alloys while in Fe-base ferritic alloys a minimum of 2 percent Al with Cr contents near 18 percent are required or much higher Al contents (>16 percent Al) if no Cr is present (e.g., Thermenol, TRW Valve). It is worth noting that no successful alumina/aluminate spinel forming commercial Co-base or Fe-base austenitic alloys have been developed.
6. The tri-rutile structure-Ni(Nb, Ta, Mo, W)$_2$O$_6$ formed on mostly alumina forming Ni-base turbine alloys particularly when significant Ta and/or Mo are present appeared to confer added cyclic oxidation resistance (e.g., NASA-VIA, B-1900, U-700).

7. Two alloys which show better than expected behavior based on their chemical composition are the Ni- and Co-base chromia formers HAS-S and HA-188 which contain trace amounts of the reactive metal La that inhibits scale spalling. IN-100, on the other hand, which should have oxidation resistance comparable to the Ni-base turbine alloy alumina formers B-1900 or NASA-VIA shows much poorer scaling behavior due to the 1 percent V present in this alloy.
8. These protective chromia or alumina scales tend to break down (e.g., fail) as in the Cr and Al are depleted triggering the formation of the less protective base metal oxides CoO, Fe_2O_3 or NiO.
9. The two NiO forming alloys NI-270 and WAZ-20 show poor and catastrophic scaling resistance respectively due to this massive metal consuming oxide.
10. Sixteen of the 68 alloys showed excellent cyclic oxidation resistance (i.e., KB4 <0.2). Of these 16 nine of the "best" had KB4 values of less than 0.1, with virtually no significant cyclic oxidation attack. They are in decreasing order of ranking: U-700 (the best), TRW-Valve, HOS-875, NASA-18T, NASA-VIA, Thermenol, IN-702, B-1900 and 18SR. Three are Ni-base alumina forming turbine alloys: U-700, NASA-VIA, and B-1900. Four are Fe-base alumina forming ferritic heater/sheet alloys with Al:HOS-875, NASA-18T, Thermenol, and 18SR. One is a Ni-base alumina forming superalloy sheet alloy IN-702.

APPENDIX A

DERIVATION AND ANALYSIS OF THE OXIDATION ATTACK PARAMETERS, KB3

The basic approach which has proven successful in other shorter cyclic time studies is to fit the specific weight change versus time data for each sample run to a simple quasi-paralinear equation by multiple linear regression:

$$\Delta W/A = k_1^{1/2} t^{1/2} + k_2 t \pm \text{S.E.E.} \tag{1}$$

Here $k_1^{1/2}$ and k_2 are constants analogous to the scale growth and scale spalling constants and S.E.E. is the standard error of estimate. If the fit is good enough (usually $R^2 > 0.90$) and $k_1^{1/2}$ is significant and positive and k_2 statistically significant, the an attack parameter K_a is defined as:

$$K_a = \left(k_1^{1/2} + 10\left|k_2\right|\right) \tag{2}$$

If $k_1^{1/2}$ is either not significant or negative, then K_a is defined as

$$K_a = 20\left|k_2\right| \tag{3}$$

The rational behind these K_a derivatives and their application in cyclic oxidation studies at this laboratory are discussed in references 4, 6 and 10 to 19. It has been shown that these K_a values are valid as estimators of oxidation resistance. However, because of the overall length of the test (10 000 hr) and the length of each exposure cycle (1000 hr) the calculation of K_a was modified as follows to obtain the same relative rating as with the one hour test cycles. This modified attack parameter KB3 is defined as:

$$KB3 = \left(k_1^{1/2} + 100\left|k_2\right|\right) \tag{4}$$

As above, if $k_1^{1/2}$ is either not significant or negative, the KB3 is defined as

$$KB3 = 250\left|k_2\right| \tag{5}$$

This gives KB3 as equivalent rankings to Ka as follows:

KB3 < 0.20	Excellent
0.20 to 0.50	Good
0.50 to 1.0	Fair
1.0 to 5.0	Poor
>5.0	Catastrophic

This permits a large number of alloys to be ranked based on a single standard.

The sixty-eight Ni-, Co-, and Fe-base alloys involving 132 individual 10 000 hr cyclic run data were each individually fitted to equation (1). The derived constant(s) were then substituted into equations (4) or (5) where applicable to generate the individual KB3's. The individual KB3 values are listed in table A-1 along with the $k_1^{1/2}$ and/or k_2 values derived from equations (3) or (4) as well as other pertinent data.

There is a direct relationship between the absolute value of the final specific weight change of each sample and its corresponding KB3 value as are listed in table A-1. This is shown in the scatter diagram in figure A-1 on a log/log plot. This gives a relatively quick ranking independent of the alloy base, without going through an elaborate series of regression analyses.

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TABLE I.—CHEMICAL ANALYSIS OF THE 68 ALLOYS TESTED FOR TEN-1000 HOUR CYCLES AT 982 CENT

Alloy Base	Alloy Type	Alloy	Ni	Co	Fe	Cr	Al	Ti	Mo	W	Nb	Ta	C	Zr	Hf	Y	Mn	S	P	Cu	Si	B	La	V
Cobalt-base	Superalloy	Belgian P-3	11.6	32.85	29.5	25	0	0	0	0	0	0	0.05	0	0	0	0	0	0	0	1	0	0	0
		H-150	3	47.63	20	28	0	0	0	0	0	0	0.12	0	0	0	0.5	0	0	0	0.75	0	0	0
		HA-188	22	39.39	1.5	22	0	0	0	14	0	0	0.08	0	0	0	0.75	0	0	0	0.2	0	0.08	0
		L-605	10	52.9	0	20	0	0	0	15	0	0	0.1	0	0	0	1.5	0	0	0	0.5	0	0	0
	Turbine alloy	Belgian S-57	10	56.5	0	25	3	0	0	0	0	5	0	0	0	0.5	0	0	0	0	0	0	0	0
		MAR-M-509	10	54.7	0	23.5	0	0.2	0	7	0	3.5	0.6	0.5	0	0	0	0	0	0	0	0	0	0
		WI-52	0	65.55	0	21	0	0	0	11	2	0	0.45	0	0	0	0	0	0	0	0	0	0	0
		X-40	10.5	56	0	25.5	0	0	0	7.5	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0
Iron-base	Austenitic stainless steel	304 S.S.	10	0	67.92	19	0	0	0	0	0	0	0.08	0	0	0	2	0	0	0	1	0	0	0
		309 S.S.	13.5	0	60.3	23	0	0	0	0	0	0	0.2	0	0	0	2	0	0	0	1	0	0	0
		310 S.S.	20.5	0	50.75	25	0	0	0	0	0	0	0.25	0	0	0	2	0	0	0	1.5	0	0	0
		316 S.S.	12	0	65.42	17	0	0	2.5	0	0	0	0.08	0	0	0	2	0	0	0	1	0	0	0
		321 S.S.	10.5	0	69.02	17	0	0.4	0	0	0	0	0.08	0	0	0	2	0	0	0	1	0	0	0
		334 S.S.	20	0	58.435	19	0.3	0.4	0	0	0	0	0.05	0	0	0	1	0.015	0.02	0.5	0.3	0	0	0
		347 S.S.	11	0	67.12	18	0	0	0	0	0.4	0.4	0.08	0	0	0	2	0	0	0	1	0	0	0
		RA-309	14	0	60.635	23	0	0	0	0	0	0	0.05	0	0	0	1.5	0.015	0.015	0	0.8	0	0	0
		RA-310	20	0	52.935	25	0	0	0	0	0	0	0.05	0	0	0	1.5	0.015	0.015	0	0.5	0	0	0
	Ferritic alloy	409 S.S.	0	0	88.45	11	0	0.5	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0
		410 S.S.	0	0	85.35	12.5	0	0	0	0	0	0	0.15	0	0	0	1	0	0	0	1	0	0	0
		430 S.S.	0	0	81.88	17	0	0	0	0	0	0	0.12	0	0	0	0	0	0	0	1	0	0	0
		Croloy 5	0	0	93.74	5	0	0	0.55	0	0	0	0.15	0	0	0	0.03	0.03	0	0	0.5	0	0	0
		Croloy 7	0	0	91.07	7	0	0	0.55	0	0	0	0.15	0	0	0	0.45	0.03	0	0	0.75	0	0	0
		Croloy 9	0	0	88.52	9	0	0	1.35	0	0	0	0.15	0	0	0	0.45	0.03	0	0	0.5	0	0	0
		RA-26-1	0.2	0	71.635	26	0	0.5	1	0	0	0	0.02	0	0	0	0.3	0.015	0.02	0	0.3	0	0	0
		T439 S.S.	0.5	0	79.25	18.25	0.15	1	0	0	0	0	0.07	0	0	0	0.35	0.03	0.3	0	0.4	0	0	0
	Ferritic alloy with Al	18SR	0.25	0	77.91	18	2	0.4	0	0	0	0	0.04	0	0	0	0.4	0	0	0	1	0	0	0
		HOS-875	0	0	71.4	22.5	5.5	0	0	0	0	0	0.1	0	0	0	0	0	0	0	0.5	0	0	0
		NASA-18T	0	0	76.546	18	2	0.5	0	0	0	1.25	0.04	0	0	0	0.4	0.014	0.007	0	1.25	0	0	0
		Thermenol	0	0	80.65	0	16	0	3.3	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0
		TRW Valve	0.1	0	66.81	0	32	0	0.1	0.5	0	0	0.04	0	0	0	0.1	0	0	0	0.35	0	0	0
	Superalloy	Incoloy-800	32	0	45.26	20.5	0.4	0.4	0	0	0	0	0.04	0	0	0	0.75	0	0	0.3	0.35	0	0	0
		Multimet	20	20	30.2	21	0	0	3	2.5	0.5	0.5	0.15	0	0	0	1.5	0	0	0	0.5	0	0	0
		RA-330	35	0	43.185	19	0	0	0	0	0	0	0.05	0	0	0	1.5	0.015	0.015	0	1.25	0	0	0
Nickel-base	Heater/Sheet alloy	Chromel A	77.97	0	0.4	20	0	0	0	0	0	0	0.03	0	0	0	0.2	0	0	0	1.4	0	0	0
		Chromel AA	67.77	0	10	20	0	0	0	0	0	0	0.03	0	0	0	0.2	0	0	0	2	0	0	0
		Chromel C	59.34	0	24	15	0	0	0	0	0	0	0.06	0	0	0	0.2	0	0	0	1.4	0	0	0
		Chromel P	89.39	0	0.2	10	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0.4	0	0	0
		DH-241	76.32	0	0.25	20	0	0	0	0	0	0	0.03	0	0	0	2	0	0	0	1.4	0	0	0
		DH-242	77.76	0	1	20	0	0	0	0	0	0	0.04	0	0	0	0.2	0	0	0	1	0	0	0
		Ni-40Cr	60	0	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Tophet 30	68.6	0	0	30	0	0	0	0	0	0	1.4	0	0	0	0	0	0	0	0	0	0	0

TABLE I.—Concluded.

Alloy Base	Alloy Type	Alloy	Ni	Co	Fe	Cr	Al	Ti	Mo	W	Nb	Ta	C	Zr	Hf	Y	Mn	S	P	Cu	Si	B	La	V
Nickel-base	Heater/Sheet alloy with Al	DH-245	74.12	0	0.7	20	3.5	0	0	0	0	0	0.08	0	0	0	0.4	0	0	0	1.2	0	0	0
		IN-601	60.25	0	14.1	23	1.35	0	0	0	0	0	0.5	0	0	0	0.3	0	0	0.25	0.25	0	0	0
		IN-702	80.52	0	0.5	15.4	3.1	0.4	0	0	0	0	0.04	0	0	0	0.04	0	0	0	0	0	0	0
	Superalloy	HAS-C-276	55.36	2.5	5.5	15.5	0	0	16	3.75	0	0	0.02	0	0	0	1	0	0	0	0.02	0	0	0.35
		HAS-G	45.82	0	19.5	22	0	0	6.5	0.5	1	1	0.03	0	0	0	1.3	0	0	2	0.35	0	0	0
		HAS-N	69.93	0.2	5	7	0	0	16.5	0	0	0	0.06	0	0	0	0.8	0	0	0	0.5	0.01	0	0
		HAS-S	67.35	0	1	15.5	0.2	0	15.5	0	0	0	0.02	0	0	0	0.2	0	0	0	0.2	0.01	0.02	0
		HAS-X	46.3	1.5	18.5	22	0	0	9	0.6	0	0	0.1	0	0	0	1	0	0	0	1	0	0	0
		IN-600	76.453	0	7.2	15.8	0	0	0	0	0	0	0.04	0	0	0	0.2	0.007	0	0.1	0.2	0	0	0
		IN-617	55.43	12.5	0	22	1	0	9	0	0	0	0.07	0	0	0	0	0	0	0	0	0	0	0
		IN-671	51.6	0	0	48	0	0.35	0	0	0	0	0.05	0	0	0	0	0	0	0	0	0	0	0
		IN-706	77.534	1	0	16	0.4	1.75	0	0	2.9	0	0.06	0	0	0	0	0	0	0	0.35	0.006	0	0
		IN-X750	73.56	0	6.75	15	0	2.5	0	0	0.85	0	0.04	0	0	0	0.7	0	0	0.3	0.3	0	0	0
		Incoloy-804	42.64	0	25.4	29.5	0.25	0.4	0	0	0	0	0.06	0	0	0	0.85	0	0	0.4	0.5	0	0	0
		RA-333	45.185	3	18	25	0	0	3	3	0	0	0.05	0	0	0	1.5	0.015	0.015	0	1.25	0	0	0
	Turbine alloy	B-1900	64.305	10	0	8	6	1	6	0.1	0.1	4.3	0.1	0.08	0	0	0	0	0	0	0	0.015	0	0
		IN-100	59.755	15	0	10	5.5	5.5	3	0	0	0	0.18	0.05	0	0	0	0	0	0	0	0.015	0	1
		IN-713 LC	74.84	0	0	12	5.9	0.6	4.5	0	2	0	0.05	0.1	0	0	0	0	0	0	0	0.01	0	0
		IN-738	61.42	8.5	0	16	3.4	3.4	1.75	2.6	0.9	1.75	0.17	0.1	0	0	0	0	0	0	0	0.01	0	0
		MAR-M-200	58.585	10	0	9	5	2	0	12.5	2.7	0	0.15	0.05	0	0	0	0	0	0	0	0.015	0	0
		NASA-VIA	62.02	7.5	0	6.1	5.4	1	2	5.8	0.5	9	0.13	0.13	0.4	0	0	0	0	0	0	0.02	0	0
		Rene 120	59.815	10	0	9	4.3	4	2	7	0	3.8	0	0.07	0	0	0	0	0	0	0	0.015	0	0
		Rene 80	64.285	9.5	0	14	3	5	4	0	0	0	0.17	0.03	0	0	0	0	0	0	0	0.015	0	0
		TAZ-8A	68.371	0	0	6	6	0	4	4	2.5	8	0.125	1	0	0	0	0	0	0	0	0.004	0	0
		U-700	54.02	18.5	0	15	4.3	3.5	4.5	0	0	0	0.07	0.08	0	0	0	0	0	0	0	0.03	0	0
		WAZ-20	74.7	0	0	0	6.5	0	0	18.5	0	0	0.15	0.15	0	0	0	0	0	0	0	0	0	0
	Unalloyed	Ni-270	99.99	0	0	0	0	0	0	0	0	0	0.01	0	0	0	0	0	0	0	0	0	0	0

TABLE II.—TEST SAMPLE DESCRIPTION AND RELATIVE RANKING BASED ON APPEARANCE

Alloy Base	Alloy Type	Alloy	Rank	Post-Test Sample Description
Cobalt	Superalloy	Belgian P-3	1	Thin coherent dark black oxide
		H-150	3	Dark green moderately thick scale;corners thicker gray glazed oxide
		HA-188	2	Fairly thin dark green slightly speckled scale
		L-605	4	Fairly thin black oxide which heavily spalls over a fairly thin bumpy black scale
	Turbine alloy	Belgian S-57	3	Moderately thick blackish scale with edge spall; slightly speckled
		MAR-M-509	3	Moderately thin bright blue-green scale with edge spall
		WI-52	4	Bright black oxide mostly spalled over a bumpy black moderately thin scale
		X-40	2	Moderately thin bright blue-green scale with some edge spall
Iron	Austenitic stainless steel	304 S.S.	5	Sample completely oxidized to a dark black thick scale; oxidized sample severly cracked
		309 S.S.	4	Moderately thick bumpy black-gray scale
		310 S.S.	4	Moderately thick bumpy black-gray scale
		316 S.S.	5	Sample completely oxidized to a dark black thick scale; oxidized sample severly cracked
		321 S.S.	5	Massive thick black glazed cracked scale
		334 S.S.	5	Dark gray pocked scale; warped and cracked
		347 S.S.	5	Lumpy massive black scale; sample cracked and broke apart
		RA-309	4	Moderately thick bumpy black scale
		RA-310	3	Moderately thin charcoal black scale
	Ferritic alloy	409 S.S.	5	Massive thick black glazed cracked scale
		410 S.S.	5	Massive thick charcoal black scale
		430 S.S.	5	Massive thick black cracked scale
		Croloy 5	5	Sample completely oxidized to a thick gray-black scale
		Croloy 7	5	Sample completely oxidized to a thick gray-black scale
		Croloy 9	5	Sample completely oxidized to a thick gray-black scale
		RA-26-1	2	Fairly thin gray-black scale
		T439 S.S.	5	Dark gray thin oxide; sample warped and cracked
	Ferritic alloy with Al	18SR	1	Thin coherent bronze scale
		HOS-875	1	Thin coherent dark brown scale
		NASA-18T	1	Thin coherent dark brown scale
		Thermenol	1	Thin coherent dark gray scale
		TRW Valve	1	Thin coherent light gray scale
	Superalloy	Incoloy-800	4	Thick black scale with edge spall
		Multimet	5	Bumpy black oxide over a thin olive-green scale with heavy spall
		RA-330	3	Moderately thin charcoal black scale
Nickel	Heater/Sheet alloy	Chromel A	2	Fairly thin green scale
		Chromel AA	2	Fairly thin greenish-black scale
		Chromel C	2	Fairly thin brownish-black scale
		Chromel P	4	Moderately thick bumpy black scale
		DH-241	2	Fairly thin dark green scale
		DH-242	2	Fairly thin dark green scale with light powderly spall
		Ni-40Cr	2	Fairly thin charcoal black scale
		Tophet 30	2	Fairly thin dark green scale
	Heater/Sheet alloy with Al	DH-245	2	Fairly thin dark charcoal black scale
		IN-601	2	Fairly thin dark black scale; a few small surface spall areas
		IN-702	1	Thin gray-green coherent scale
	Superalloy	HAS-C-276	4	Moderately thick olive-black scale with edge and surface spall
		HAS-G	4	Moderately thick bumpy black scale
		HAS-N	5	Thin bumpy black scale but massive spall leaves a very thin sample
		HAS-S	3	Moderately thick black-green scale
		HAS-X	2	Fairly thin dark brownish-black slightly speckled scale
		IN-600	3	Moderately thick dark black scale with significant edge and surface spall
		IN-617	2	Fairly thin dull dark black coherent scale
		IN-671	1	Thin charcoal black coherent scale
		IN-706	4	Moderately thick black scale with a large amount of spall
		IN-X750	3	Moderately thick bumpy black scale
		Incoloy-804	3	Moderately thick black scale with edge spall
		RA-333	3	Moderately thick charcoal brownish-black scale
	Turbine alloy	B-1900	1	Thin coherent dark blue-green scale
		IN-100	3	Fairly thick slate gray coherent scale
		IN-713 LC	1	Thin gray blue-green coherent scale
		IN-738	3	Moderately thick bumpy green-black scale
		MAR-M-200	3	Fairly thin patchy blackish-green scale which spalls overlaying a thin black scale
		NASA-VIA	1	Thin aqua-green coherent scale
		Rene 120	2	Fairly thin black scale with slight edge spall
		Rene 80	5	Moderately thick bumpy olive-black scale left after massive spall
		TAZ-8A	2	Thin dark green coherent slightly speckled scale
		U-700	1	Thin dark olive coherent scale
		WAZ-20	5	Massive thick black scale
	Unalloyed	Ni-270	4	Thick bright sparkling black coherent scale

Appearance Ranking: (1) Excellent; (2) Good; (3) Fair; (4) Poor; (5) Catastrophic

TABLE III.—X-RAY DIFFRACTION RESULTS ON TEST SAMPLES (1 = MAXIMUM RELATIVE INTENSITY)

Alloy Base	Alloy Type	Alloy	Solid Solution	Cr_2O_3	Al_2O_3	NiO	SiO_2	Fe_2O_3	$Ni(W,Mo)O_4$	Spinel(s)	Rutile-TriRutile	Other
Cobalt	Superalloy	Belgian P-3	Cobalt S.S.	2						1-ao=8.45		
		H-150	"	2						1-ao=8.40		
		HA-188	"	2						1-ao=8.40		
		L-605	"	2						1-ao=8.25		
	Turbine alloy	Belgian S-57	"							1-ao=8.35; 2-ao=8.15	3-d=3.35(TaO_2)?	
		MAR-M-509	"	1						2-ao=8.30		
		WI-52	"	1						2-ao=8.30	3-d=3.31	
		X-40	"	1						2-ao=8.30		
Iron	Austenitic stainless steel	304 S.S.	No Lines					1		2-ao=8.40		
		309 S.S.	"	2						1-ao=8.30		
		310 S.S.	"					2		1-ao=8.40		
		316 S.S.	"	2						1-ao=8.40		
		321 S.S.	"					2		1-ao=8.35		
		334 S.S.	"	2						1-ao=8.35		
		347 S.S.	Too Lumpy for XRD									
		RA-309	No Lines	2						1-ao=8.40		
		RA-310	"	2						1-ao=8.40		
	Ferritic alloy	409 S.S.	"					2		1-ao=8.40		
		410 S.S.	"					1				
		430 S.S.	"					1				
		Croloy 5	"					1				
		Croloy 7	"					1				
		Croloy 9	"					1				
		RA-26-1	Alpha Iron	1						2-ao=8.40		
		T439 S.S.	No Lines					1				
	Ferritic alloy with Al	18SR	Alpha Iron		1							2-TiO_2
		HOS-875	"		1					1-ao=8.20		
		NASA-18T	"		1					3-ao=8.15	2-d=3.25	
		Thermenol	"	2	1							
		TRW Valve	"		1							
	Superalloy	Incoloy-800	Gamma Iron							1-ao=8.45	3-d=3.27	2-$(Fe,Cr)_2O_3$
		Multimet	No Lines	2					3	1-ao=8.35		
		RA-330	No Lines	2						1-ao=8.45		
Nickel	Heater/Sheet alloy	Chromel A	Nickel S.S.	2			3			1-ao=8.35		
		Chromel AA	"	1			3			2-ao=8.30		
		Chromel C	"	2			3			1-ao=8.35		
		Chromel P	No Lines			1						
		DH-241	Nickel S.S.	1			3			2-ao=8.40		
		DH-242	"	1						1-ao=8.30		
		Ni-40Cr	"	1								
		Tophet 30	"	1						2-ao=8.30		
	Heater/Sheet alloy with Al	DH-245	"			1				2-ao=8.30; 3-ao=8.10		
		IN-601	"	1						2-ao=8.40		
		IN-702	"			1				2-ao=8.25; 3-ao=8.10		

(1) Solid Solution-No lines implies the scale is too thick to detect the base metal.
(2) Spinel(s)-ao is the lattice parameter in angstroms; ao = 8.05 to 8.15 Aluminate Spinels; ao = 8.20 to 8.40 Chromite Spinels
(3) Rutile-TriRutile-Lattice spacing, d on (110).

TABLE III.—Concluded.

Alloy Base	Alloy Type	Alloy	Solid Solution	Cr2O3	Al2O3	NiO	SiO2	Fe2O3	Ni(W,Mo)O4	Spinel(s)	Rutile-TriRutile	Other
Nickel	Superalloy	HAS-C-276	No Lines	2						1-ao=8.35		
		HAS-G	Nickel S.S.	1						2-ao=8.30		
		HAS-N	“	3								1-NiMoO4; 2-MoO4
		HAS-S	“	2						1-ao=8.35		
		HAS-X	“	2						1-ao=8.35		
		IN-600	“	2						1-ao=8.35		
		IN-617	“	1						2-ao=8.35		
		IN-671	“	1						2-ao=8.40		
		IN-706	No Lines							1-ao=8.35		
		IN-X750	Nickel S.S.	2						1-ao=8.35	3-d=3.30	
		Incoloy-804	“	2						1-ao=8.40; 3-ao=8.30		
		RA-333	“	2						1-ao=8.45		
	Turbine alloy	B-1900	Gamma/Gamma'		3					1-ao=8.10; 2-ao=8.20	4-d=3.29	
		IN-100	“				4		3	1-ao=8.10; 2-ao=8.25		
		IN-713 LC	“		2					1-ao=8.10; 3-ao=8.30		
		IN-738	“	2	4		3			1-ao=8.30; 5-ao=8.15	6-d=3.27	
		MAR-M-200	“		4	1				2-ao=8.20; 3-ao=8.10	5-d=3.28	
		NASA-VIA	“		3					1-ao=8.10	2-d=3.26	
		Rene 120	“			2				1-ao=8.30	2-d=3.21	
		Rene 80	Nickel S.S.(?)	1								
		TAZ-8A	Gamma/Gamma'		3					1-ao=8.10	2-d=3.31	
		U-700	“		1					2-ao=8.20	3-d=3.25	
		WAZ-20	No Lines			1						
	Unalloyed	Ni-270	“			1						

(1) Solid Solution-No lines implies the scale is too thick to detect the base metal.
(2) Spinel(s)-ao is the lattice parameter in angstroms; ao = 8.05 to 8.15 Aluminate Spinels; ao = 8.20 to 8.40 Chromite Spinels
(3) Rutile-TriRutile-Lattice spacing, d on (110).

TABLE IV.—MODIFIED OXIDATION ATTACK PARAMETER-KB4-RATINGS (LISTED IN DESCENDING ORDER FROM “BEST” to “WORST”)

Alloys	KB4-1	KB4-2	KB4-3	KB4-4	KB4-Max	Rating
U-700	0.005300	0.005690			0.005690	Excellent
TRW Valve	0.014131	0.013693			0.014131	“
HOS-875	0.024796	0.019181			0.024796	“
NASA-18T	0.036742	0.024412			0.036742	“
NASA-VIA	0.027900	0.038300			0.038300	“
Thermenol	0.035797	0.041846			0.041846	“
IN-702	0.058880	0.051002			0.058880	“
B-1900	0.076700	0.067900			0.076700	“
18SR	0.096802	0.099733			0.099733	“
X-40	0.106634				0.106634	“
HAS-S	0.129085	0.130955			0.130955	“
Chromel A	0.136620				0.136620	“
DH-245	0.142373	0.126351			0.142373	“
H-150	0.176100	0.128400			0.176100	“
P-3	0.178400	0.151470			0.178400	“
RA-333	0.181500				0.181500	“
Tophet 30	0.204226	0.207581			0.207581	Good
RA-310	0.209950	0.216320			0.216320	“
Chromel AA	0.220693				0.220693	“
HA-188	0.258060	0.240790			0.258060	“
IN-713LC	0.250000	0.259600			0.259600	“
TAZ-8A	0.169730	0.264660			0.264660	“
S-57	0.272148	0.267600			0.272148	“
IN-617	0.290774	0.264319	0.270380		0.290774	“
Chromel C	0.310783				0.310783	“
IN-601	0.316063	0.329923			0.329923	“
RA-26-1	0.334730	0.253220			0.334730	“
HAS-X	0.328471	0.351890			0.351890	“
IN-671	0.353880	0.218600			0.353880	“
Rene-120	0.355630	0.322410	0.167420		0.355630	“
In.-800	0.359604	0.376152	0.310104		0.376152	“
DH-241	0.404250				0.404250	“
Ni-40Cr	0.414601	0.427262			0.427262	“
RA-330	0.278856	0.496620	0.467208		0.496620	“
DH-242	0.499070	0.501930			0.501930	Fair
MAR-M-509	0.588360				0.588360	“
MAR-M-200	0.598560	0.331680			0.598560	“
IN-600	0.691308	0.730980			0.730980	“
IN-706	0.628290	0.801190			0.801190	“
IN-738	1.084800	1.316760			1.316760	Poor
HAS-C-276	1.100710	1.402440	1.297400	1.187940	1.402440	“
NI-270	1.482170	1.729010			1.729010	“
334S.S.	2.376220	2.260580			2.376220	“
IN-750X	2.022504	2.514768			2.514768	“
Chromel P	2.302937	2.942576			2.942576	“
In.-804	2.896752	3.104040			3.104040	“
HAS-G	3.835910	3.751540			3.835910	“
310S.S.	3.911960	3.762590			3.911960	“
L-605	3.214120	4.467190			4.467190	“
309S.S.	5.032300	4.091100			5.032300	Catastrophic
WAZ-20	5.629260				5.629260	“
RA-309	5.007340	5.692180			5.692180	“
Rene-80	7.956340	8.258600			8.258600	“
WI-52	8.933951				8.933951	“
IN-100	9.52152	11.30760			11.30760	“
Multimet	12.532338	12.773278			12.773278	“
HAS-N	15.437940	15.473640			15.473640	“
304S.S.	18.138400	16.351300			18.138400	“
T439S.S.	12.184900	20.794200			20.794200	“
321S.S.	18.236820	21.289800	12.569900		21.289800	“
409S.S.	25.443180	18.109000			25.443180	“
347S.S.	30.314900				30.314900	“
316S.S.	9.232020	36.963080			36.963080	“
430S.S.	36.008000	57.088220			57.088220	“
410S.S.	72.865520	72.203600			72.865520	“
Croloy 9	107.058700	108.273620			108.273620	“
Croloy 5	108.952900				108.952900	“
Croloy 7	109.688600	109.120900			109.688600	“

TABLE AI.—SUMMARY OF ALLOY TEST SAMPLE GRAVIMETRIC DATA

Base	Type	Alloy	Run No.	Test Time, Hrs	Model Fit	k1**1/2	k2	KB3	R**2	Final W/A	Thick., mm
Cobalt	Superalloy	Belgian P-3	706-1	10000	Paralinear	0.095099	-0.0008330	0.17840	0.985	1.100	2.249
		"	706-2	"	"	0.080820	-0.0007065	0.15147	0.989	0.963	2.259
		H-150	717-5	"	Linear		0-9000hrs. -.000587	0.14675	0.936	-4.672	1.691
		"	717-6	"	"		0-9000hrs. -.000428	0.10700	0.913	-3.277	1.680
		HA-188	705-5	"	Paralinear	0.091583	-0.0014298	0.23460	0.996	-4.865	1.636
		"	705-6	"	"	0.089288	-0.0012956	0.21890	0.996	-4.172	1.633
		L-605	705-3	"	"	0.965065	-0.0150736	2.47240	0.861	-69.733	1.350
		"	705-4	"	"	1.323318	-0.0211294	3.43630	0.878	-101.812	1.356
	Turbine alloy	Belgian S-57	705-1	"	"	0.063754	0-8000hrs. -.001630	0.22679	0.987	-5.343	1.671
		"	705-2	"	"	0.059953	0-9000hrs. -.0016305	0.22300	0.986	-7.985	1.708
		MAR-M-509	726-1	"	Linear		k2avg|.0017161|	0.49030		-1.530	2.508
		WI-52	706-3	"	Paralinear	1.250612	-0.0562166	6.87227	0.996	-413.719	2.680
		X-40	706-4	"	"	0.043814	-0.0005313	0.09694	0.850	-0.788	2.529
Iron	Austenitic stainless steel	304 S.S.	727-3	"	Linear		0-8000hrs. -.051824	12.95600		-183.973	3.119
		"	727-4	"	"		0-9000hrs. -.046718	11.67950		-227.652	3.150
		309 S.S.	723-4	"	Paralinear	1.087441	-0.0278358	3.87100	0.982	-184.967	1.628
		"	723-5	"	"	0.716349	-0.0243061	3.14700	0.991	-187.092	1.625
		310 S.S.	722-3	"	"	1.091408	-0.0191775	3.00920	0.935	-92.361	1.570
		"	722-4	"	"	1.045038	-0.0184926	2.89430	0.937	-86.424	1.578
		316 S.S.	723-2	"	Linear		k2avg.|.026377|	6.59430		109.584	1.491
		"	723-3	"	"		k2avg.|.105609|	26.40220		-51.306	1.517
		321 S.S.	722-5	"	"		k2avg.|.052105|	13.02630		34.922	1.503
		"	722-6	7000	"		k2avg.|.060828|	15.20700		112.184	1.280
		"	726-3	10000	"		k2avg.|.035914|	8.97850		-19.042	1.296
		334 S.S.	725-5	"	"		0-8000hrs. .006789	1.69730	0.957	61.051	0.461
		"	725-6	"	"		0-8000hrs. .006459	1.61470	0.970	63.035	0.459
		347 S.S.	723-1	9000	"		0-2000hrs. .086614	21.65350	0.997	178.173	1.474
		RA-309	724-1	10000	Paralinear	1.000288	0-9000hrs. -.028515	3.85180	0.995	-169.717	2.735
		"	724-2	"	"	1.240970	0-9000hrs. -.031376	4.37860	0.993	-176.647	2.740
		RA-310	725-1	"	Paralinear	0.083301	-0.0007817	0.16150	0.990	0.264	2.718
		"	725-2	"	"	0.086218	-0.0008014	0.16640	0.997	0.500	2.720
	Ferritic alloy	409 S.S.	719-1	"	Linear		0-3000hrs. .072695	18.17370	0.988	184.589	1.471
		"	719-2	"	"		0-2000hrs. |.051740|	12.93500		96.963	1.478
		410 S.S.	721-3	"	"		0-1000hrs. .208190	52.04680		208.562	1.605
		"	721-4	"	"		0-1000hrs. .206300	51.57400		206.774	1.607
		430 S.S.	718-1	"	"		0-2000hrs. .102880	25.72000	0.991	216.138	1.591
		"	718-2	"	"		0-1000hrs. -.163109	40.77730		-164.645	1.594
		Croloy 5	719-5	"	"		0-1000hrs. .311294	77.82350		310.631	2.334
		Croloy 7	719-3	"	"		0-1000hrs. .313396	78.34900		315.068	2.343
		"	719-4	"	"		0-1000hrs. .311774	77.94350		312.532	2.350
		Croloy 9	718-5	"	"		0-1000hrs. .305882	76.47050		305.265	2.320
		"	718-6	"	"		0-1000hrs. .309353	77.33830		308.470	2.330
		RA-26-1	720-1	"	Paralinear	0.058899	-0.0024544	0.30430	0.975	-18.655	2.290
		"	720-2	"	"	0.027473	-0.0020271	0.23020	0.971	-17.594	2.271
		T439 S.S.	721-5	"	Linear		0-2000hrs .034814	8.70350	0.927	59.984	0.399
		"	721-6	"	"		0-1000hrs. .059412	14.85300		59.577	0.398
	Ferritic alloy with Al	18SR	721-1	"	Paralinear	0.063452	-0.0003335	0.09680	0.998	3.467	1.698
		"	721-2	"	"	0.065193	-0.0003454	0.09973	0.999	3.202	1.700
		HOS-875	718-3	"	"	0.016496	-0.0000830	0.02480	0.998	0.830	1.299
		"	718-4	"	"	0.013701	-0.0000548	0.01918	0.998	0.811	1.300
		NASA-18T	720-5	"	"	0.024012	-0.0001273	0.03674	0.992	1.254	1.341
		"	720-6	"	"	0.017072	-0.0000734	0.02441	0.994	1.073	1.190
		Thermenol	720-3	"	"	0.025437	-0.0001036	0.03580	0.999	1.571	1.371
		"	720-4	"	"	0.028646	-0.0001320	0.04185	0.992	1.697	1.281
		TRW Valve	701-3	"	Parabolic	0.014131		0.01413	0.964	1.470	2.280
		"	701-4	"	"	0.013693		0.01369	0.993	1.333	2.440
	Superalloy	Incoloy-800	722-1	"	Paralinear	0.095083	-0.0020459	0.29967	0.990	-9.619	3.090
		"	722-2	"	"	0.102460	-0.0021100	0.31346	0.992	-9.667	3.105
		"	724-3	"	"	0.084059	-0.0017436	0.25842	0.997	-9.138	3.090
		Multimet	726-4	"	"	2.983433	-0.0596824	8.95167	0.989	-307.808	2.052
		"	726-5	"	"	2.971756	-0.0615201	9.12377	0.993	-320.822	2.042
		RA-330	723-6	"	Linear		-0.0009295	0.23238	0.993	-9.717	2.775
		"	725-3	"	Paralinear	0.208050	-0.0020581	0.41386	0.993	0.208	2.642
		"	725-4	"	"	0.203327	-0.0018601	0.38934	0.991	1.317	2.642
Nickel	Heater/Sheet alloy	Chromel A	708-3	"	Linear		-0.0004968	0.12420	0.989	-5.104	1.311
		Chromel AA	717-1	"	Paralinear	0.025254	-0.0017538	0.20063	0.999	-14.702	0.779
		Chromel C	717-2	"	Linear		-0.0011301	0.28253	0.977	-11.645	0.811
		Chromel P	715-5	"	Paralinear	1.215145	-0.0055635	1.77149	0.955	62.723	0.780

TABLE AI.—Concluded.

Base	Type	Alloy	Run No.	Test Time, Hrs	Model Fit	k1**1/2	k2	KB3	R**2	Final W/A	Thick., mm
Nickel	Heater/Sheet alloy	Chromel P	715-6	10000	Paralinear	1.527357	-0.0073616	2.26352	0.954	75.700	0.811
		DH-241	708-2	"	Linear		-0.0014700	0.36750	0.901	-12.071	1.630
		DH-242	714-1	"	"		-0.0018148	0.45370	0.999	-17.760	1.598
		"	714-2	"	"		-0.0018252	0.45630	0.999	-17.782	1.600
		Ni-40Cr	715-3	"	Paralinear	0.080773	-0.0029614	0.37691	0.999	-21.901	1.750
		"	715-4	"	"	0.086662	-0.0030176	0.38842	0.999	-21.792	1.751
		Tophet 30	707-1	"	"	0.035267	-0.0015039	0.18566	0.979	-12.209	2.605
		"	707-2	"	"	0.044462	-0.0014425	0.18871	0.982	-9.761	2.602
	Heater/Sheet alloy with Al	DH-245	708-4	"	"	0.067121	-0.0006231	0.12943	0.962	0.739	2.042
		"	708-5	"	"	0.058998	-0.0005586	0.11486	0.955	0.401	2.050
		IN-601	715-1	"	"	0.158108	-0.0012922	0.28733	0.999	2.708	1.568
		"	715-2	"	"	0.160823	-0.0013911	0.29993	0.999	2.158	1.568
		IN-702	709-5	"	"	0.032114	-0.0002677	0.05888	0.995	0.618	2.396
		"	709-6	"	"	0.029179	-0.0002182	0.05100	0.997	0.799	2.385
	Superalloy	HAS-C-276	709-3	"	"	0.348282	-0.0049842	0.84670	0.742	-23.242	1.975
		"	709-4	"	"	0.433413	-0.0064543	1.07880	0.801	-30.412	1.977
		"	716-1	"	"	0.382331	-0.0061568	0.99800	0.855	-34.356	2.000
		"	716-2	"	"	0.344629	-0.0056913	0.91380	0.869	-32.407	1.980
		HAS-G	716-5	"	"	1.042061	-0.0190859	2.95070	0.959	-96.204	1.571
		"	716-6	"	"	1.013827	-0.0187201	2.88580	0.968	-93.166	1.569
		HAS-N	716-3	8000	"	2.078101	-0.0894901	11.02710	0.998	-509.489	1.608
		"	716-4	8000	"	2.085439	-0.0896712	11.05260	0.998	-511.916	1.608
		HAS-S	707-5	10000	"	0.051427	-0.0006592	0.11735	0.921	-1.717	0.519
		"	707-6	"	"	0.052624	-0.0006643	0.11905	0.901	-1.663	0.530
		HAS-X	709-1	"	"	0.113153	-0.0018546	0.29861	0.991	-7.000	2.488
		"	709-2	"	"	0.124111	-0.0019579	0.31990	0.981	-6.918	2.498
		IN-600	708-6	"	"	0.135738	-0.0044035	0.57609	0.998	-29.330	1.608
		"	726-2	9000	"	0.147604	-0.0046155	0.60915	0.998	-26.872	1.612
		IN-617	714-4	10000	"	0.113347	-0.0015099	0.26434	0.966	-3.146	3.044
		"	714-5	"	"	0.101340	-0.0013895	0.24029	0.957	-3.233	3.046
		"	714-6	"	"	0.119515	-0.0012628	0.24580	0.969	-1.083	1.585
		IN-671	714-3	"	Linear		-0.0014155	0.35388	0.912	-11.024	3.172
		"	719-6	"	"		-0.0008744	0.21860	0.980	-0.039	3.129
		IN-706	717-3	"	"		-0.0019330	0.48330	0.859	-10.571	1.069
		"	717-4	"	"		-0.0024651	0.61630	0.930	-19.736	1.069
		IN-X750	707-3	"	Paralinear	0.581085	-0.0110434	1.68542	0.981	-58.469	1.642
		"	707-4	"	"	0.674244	-0.0142140	2.09564	0.990	-80.816	1.641
		Incoloy-804	724-5	"	"	0.917455	-0.0149651	2.41396	0.859	-80.448	1.280
		"	724-6	"	"	0.895851	-0.0169085	2.58670	0.963	-93.809	1.285
		RA-333	724-4	"	"	0.021478	-0.0014352	0.16500	0.998	-12.346	2.728
	Turbine alloy	B-1900	702-1	"	"	0.030358	-0.0004630	0.07670	0.965	-1.385	2.710
		"	702-2	"	"	0.023588	-0.0004430	0.06790	0.976	-1.830	2.690
		IN-100	704-3	"	"	2.991189	-0.0494336	7.93460	0.908	-241.946	2.431
		"	704-4	"	"	2.900761	-0.0652224	9.42300	0.997	-362.876	2.325
		IN-713LC	704-1	"	"	0.084738	-0.0016526	0.25000	0.991	-8.674	2.148
		"	704-2	"	"	0.095089	-0.0016453	0.25960	0.981	-7.635	2.149
		IN-738	703-3	"	"	0.032872	-0.0087115	0.90400	0.991	-87.697	2.275
		"	703-4	"	"	0.106466	-0.0099085	1.09730	0.990	-96.508	2.249
		MAR-M-200	701-5	"	"	0.165602	-0.0033320	0.49880	0.961	-14.230	2.328
		"	701-6	"	"	0.077998	-0.0019840	0.27640	0.965	-10.105	2.311
		NASA-VIA	703-5	"	"	0.012956	-0.0001489	0.02790	0.691	-0.078	2.352
		"	703-6	"	"	0.025888	-0.0001240	0.03830	0.997	1.415	2.352
		Rene 120	702-3	"	"	0.161505	-0.0016180	0.32330	0.908	-1.856	0.800
		"	702-4	"	"	0.143607	-0.0014950	0.29310	0.868	-2.048	0.763
		"	702-5	"	"	0.078669	-0.0007350	0.15220	0.785	-1.247	0.761
		Rene 80	701-1	"	"	1.639143	-0.0404400	5.68310	0.999	-239.296	1.722
		"	701-2	"	"	1.751044	-0.0414800	5.89900	0.999	-239.972	1.780
		TAZ-8A	703-1	"	"	0.083172	-0.0007117	0.15430	0.981	0.701	2.400
		"	703-2	"	"	0.107215	-0.0013339	0.24060	0.791	-4.113	2.339
		U-700	704-5	"	"	0.003990	-0.0000131	0.00530	0.935	0.324	1.752
		"	704-6	"	Parabolic	0.005685		0.00569	0.971	0.634	1.760
		WAZ-20	702-6	"	Paralinear	3.049076	-0.0128110	4.33020	0.999	178.286	2.701
	Unalloyed	Ni-270	706-1	"	Parabolic	1.140135		1.14013	0.999	114.002	1.442
		"	706-2	"	Paralinear	1.147125	-0.0018288	1.33001	0.999	95.915	1.443

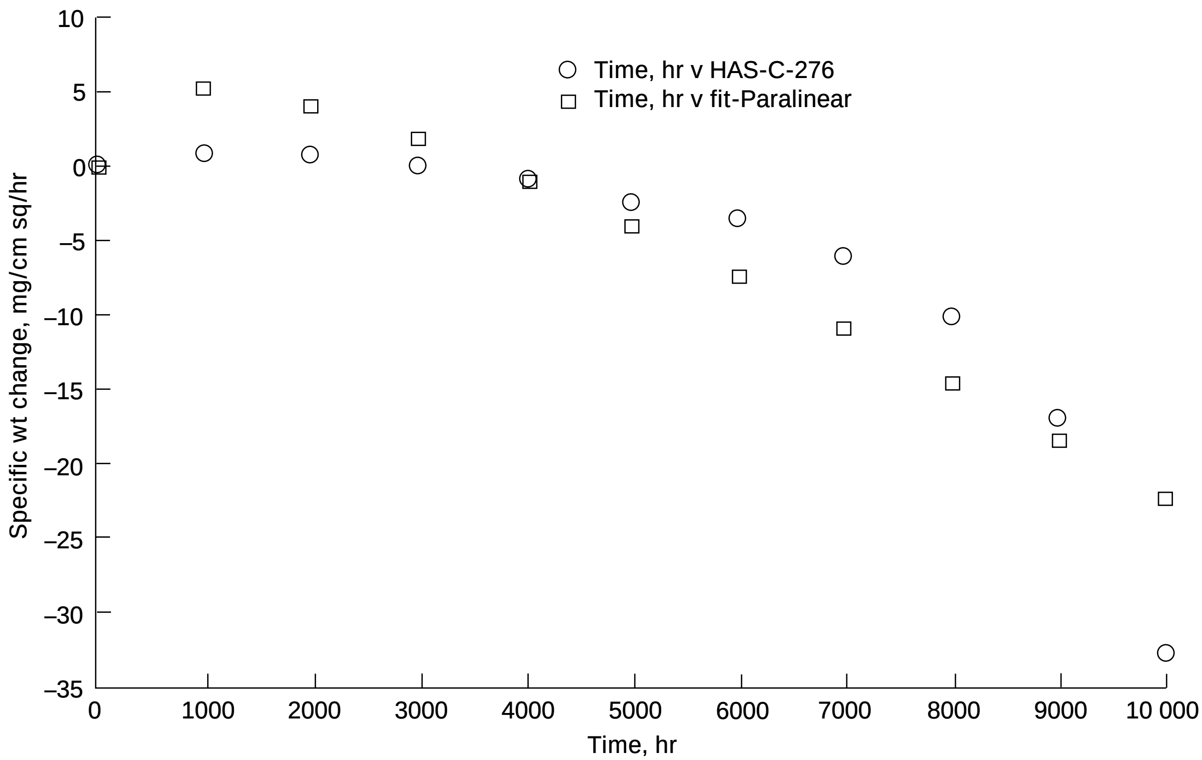

Figure 1.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample HAS-C-276.

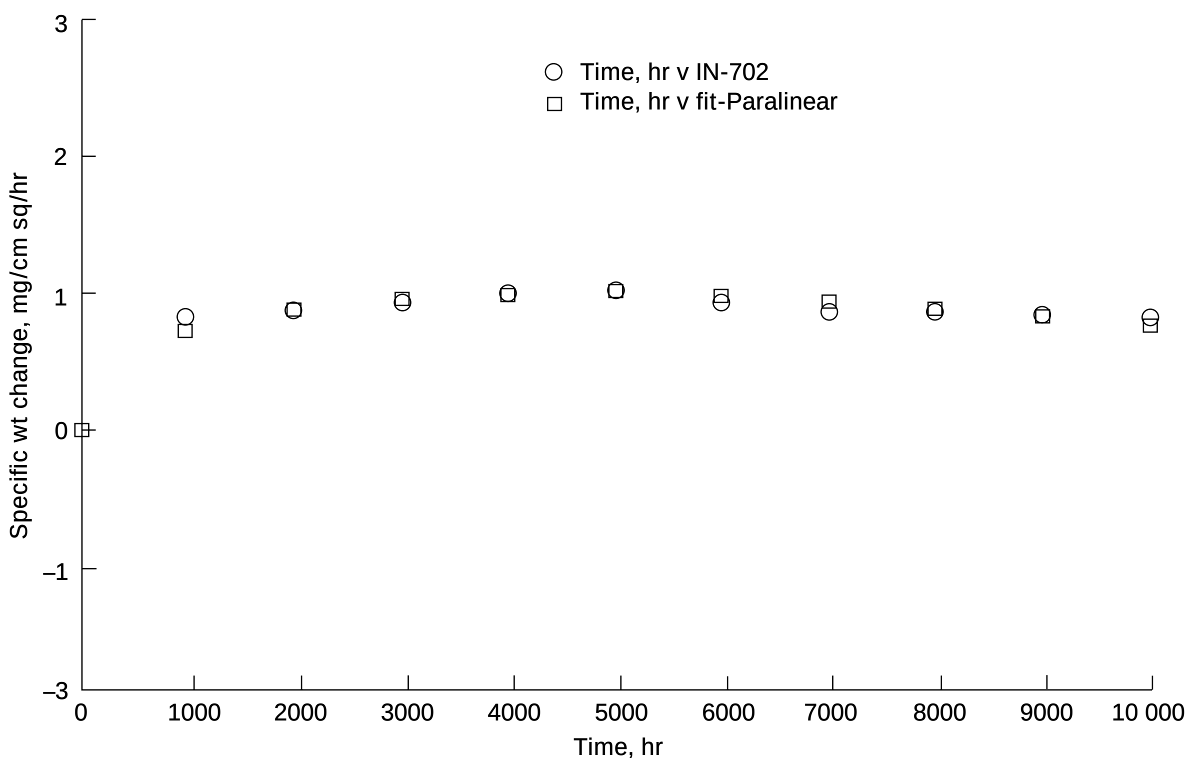

Figure 2.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample IN-702.

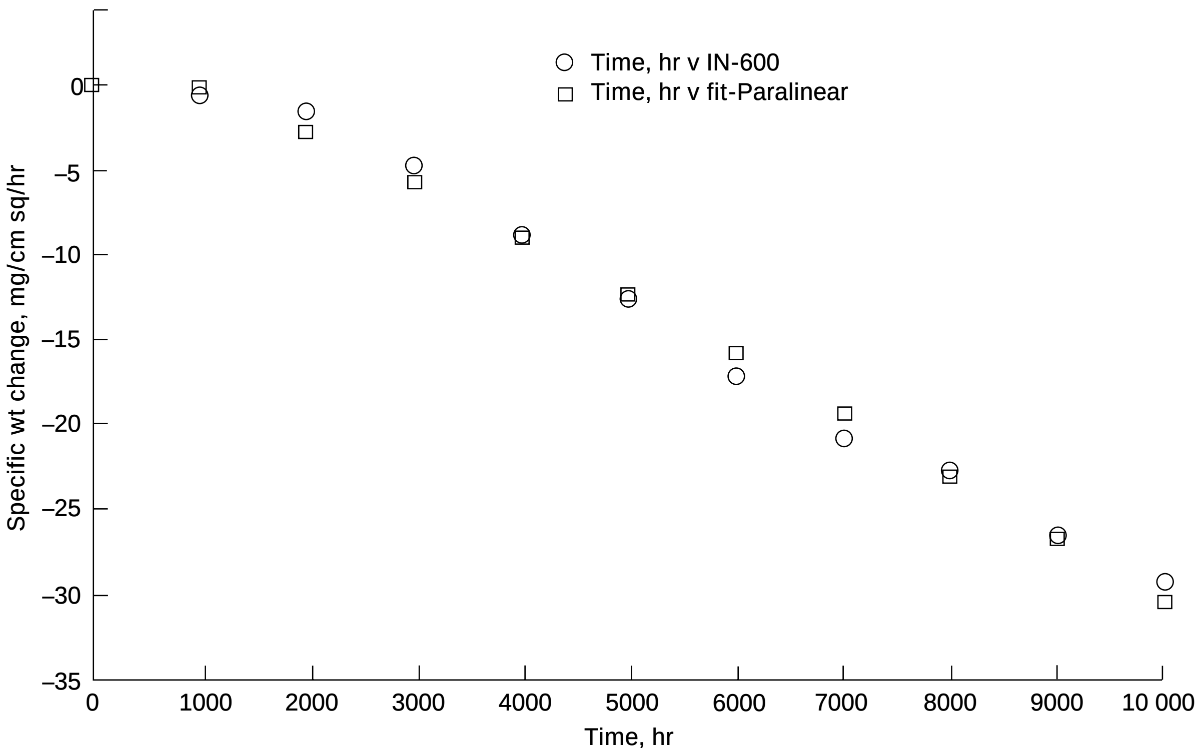

Figure 3.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample IN-600.

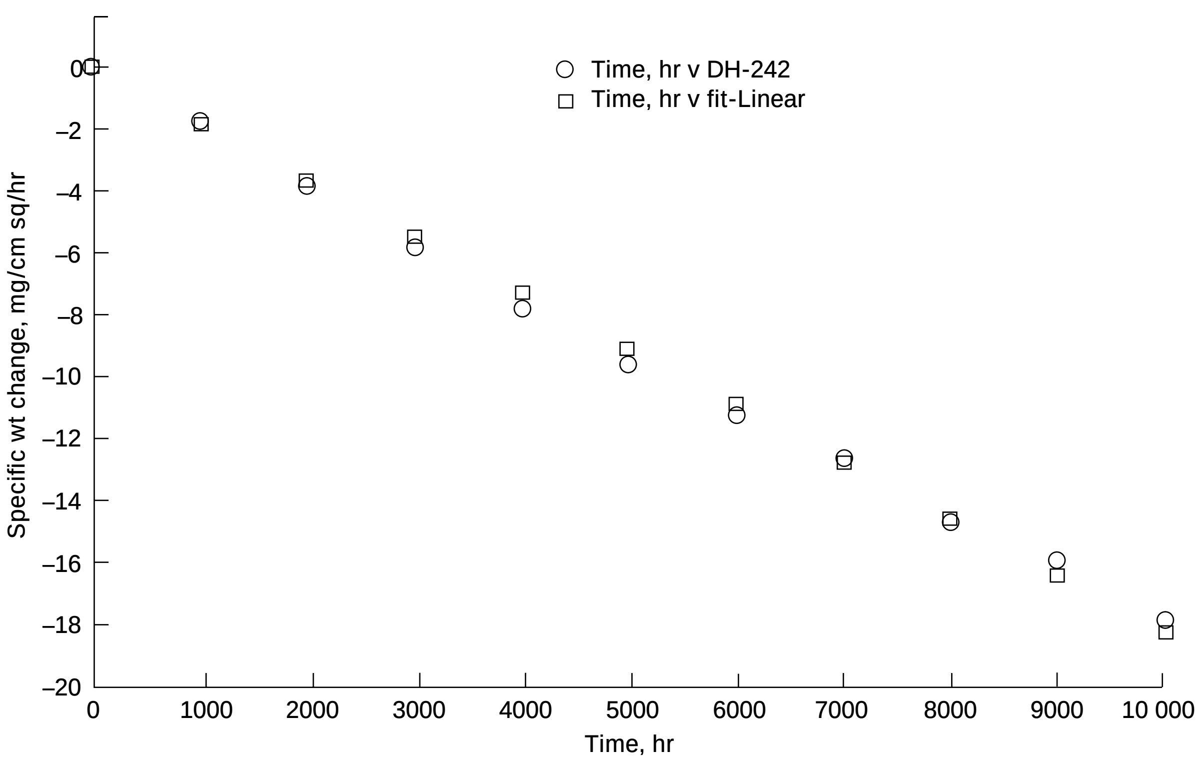

Figure 4.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample DH-242.

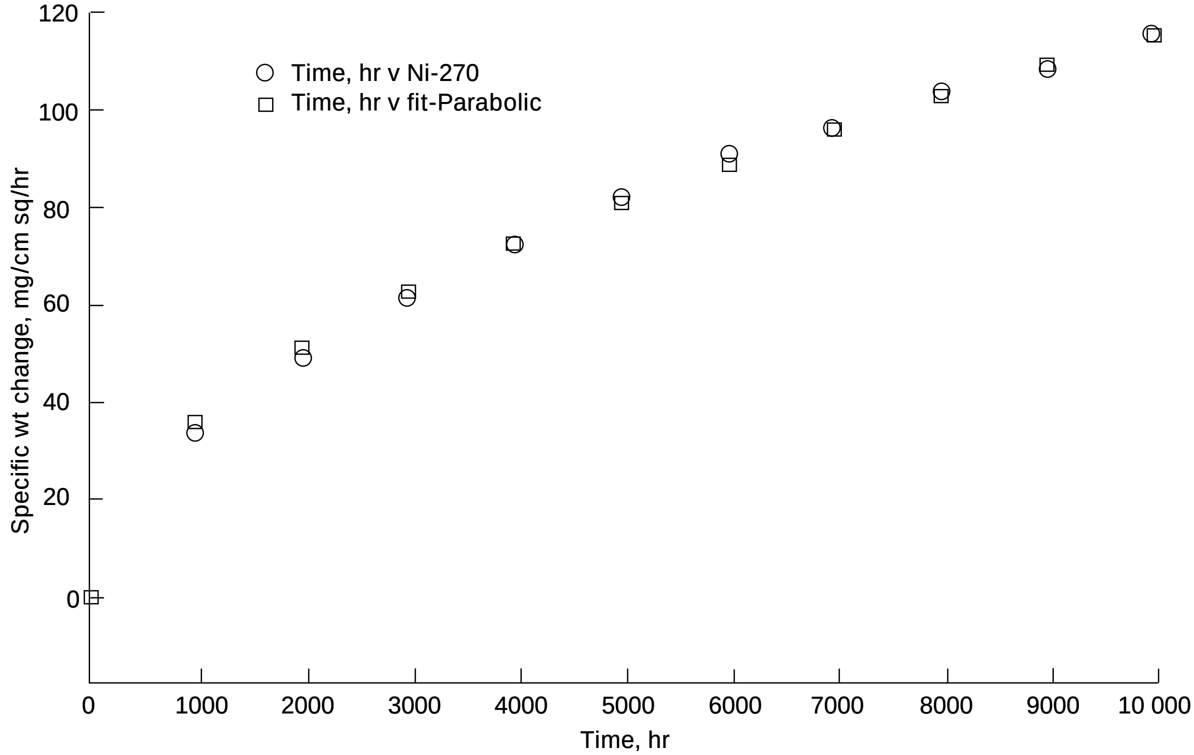

Figure 5.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample Ni-270.

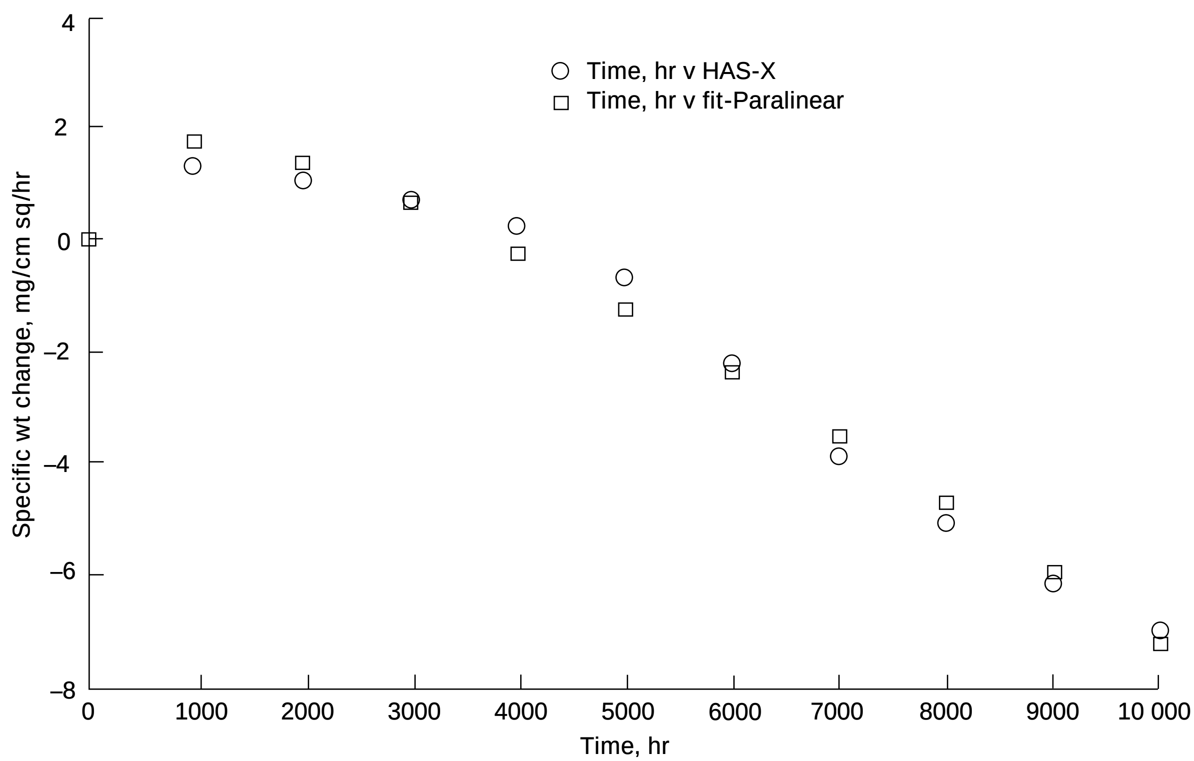

Figure 6.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample HAS-X.

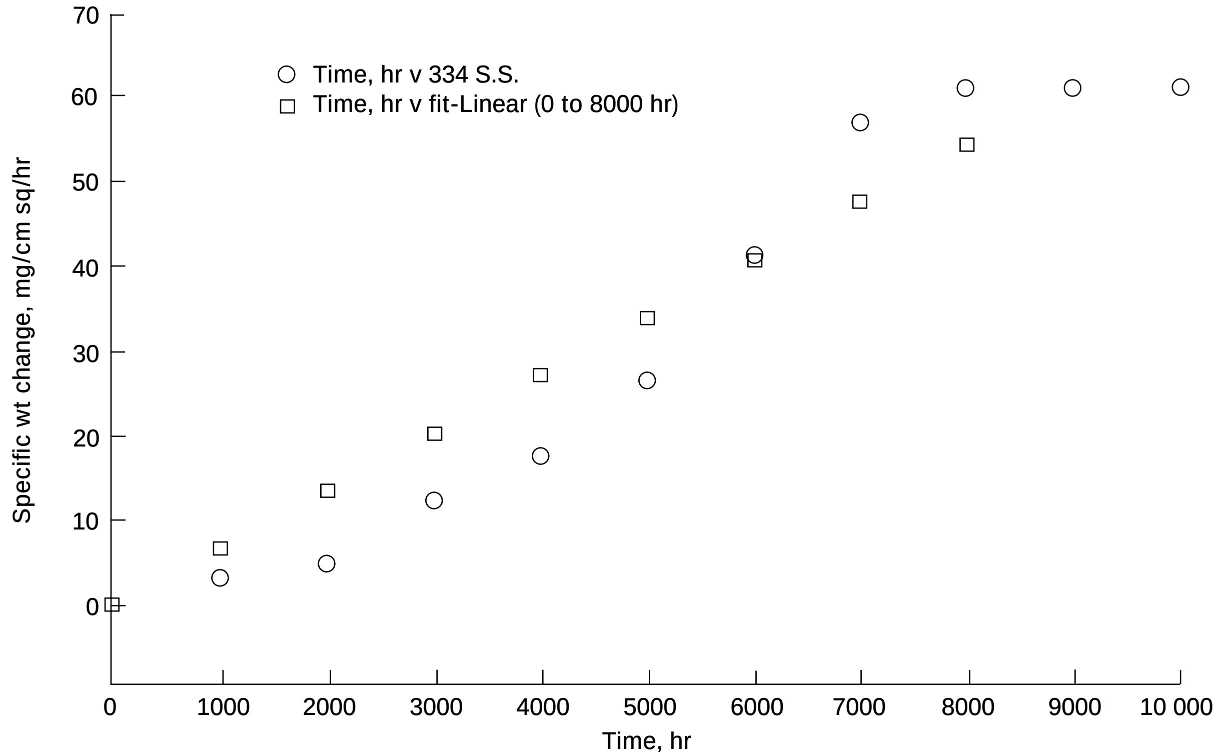

Figure 7.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Fe-base alloy sample 334 S.S.

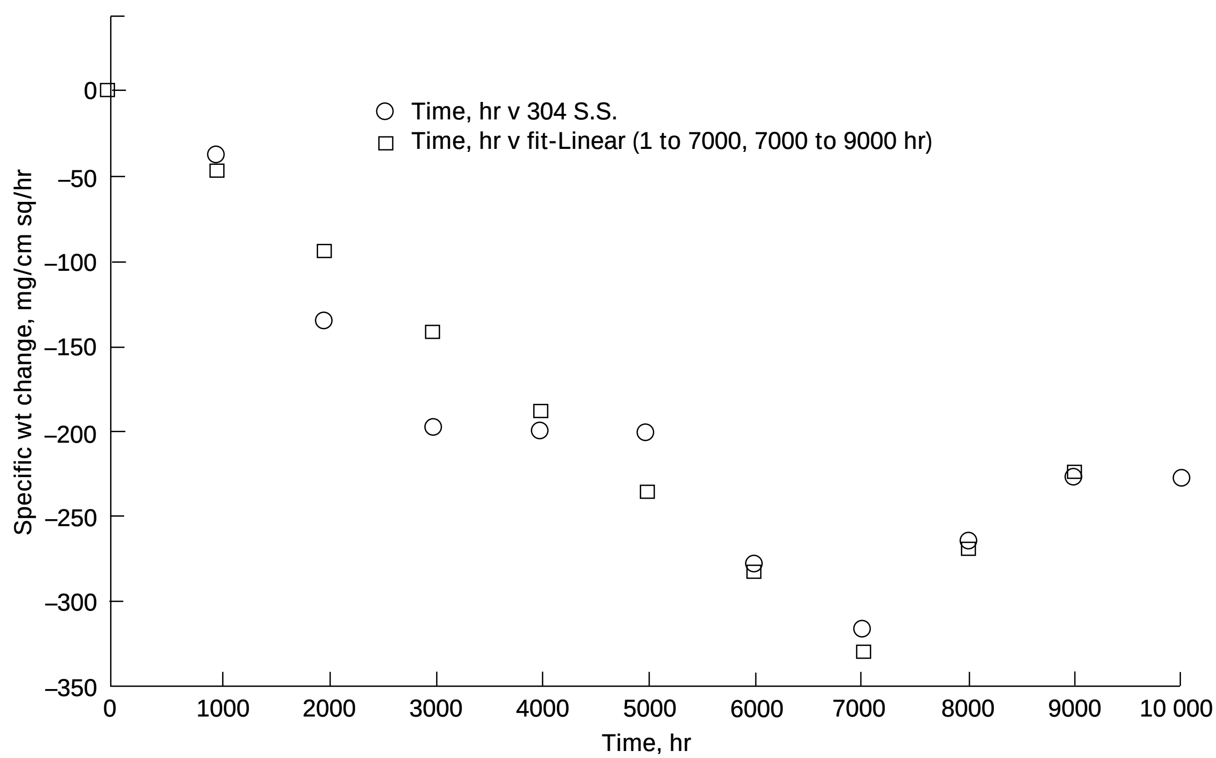

Figure 8.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Fe-base alloy sample 304 S.S.

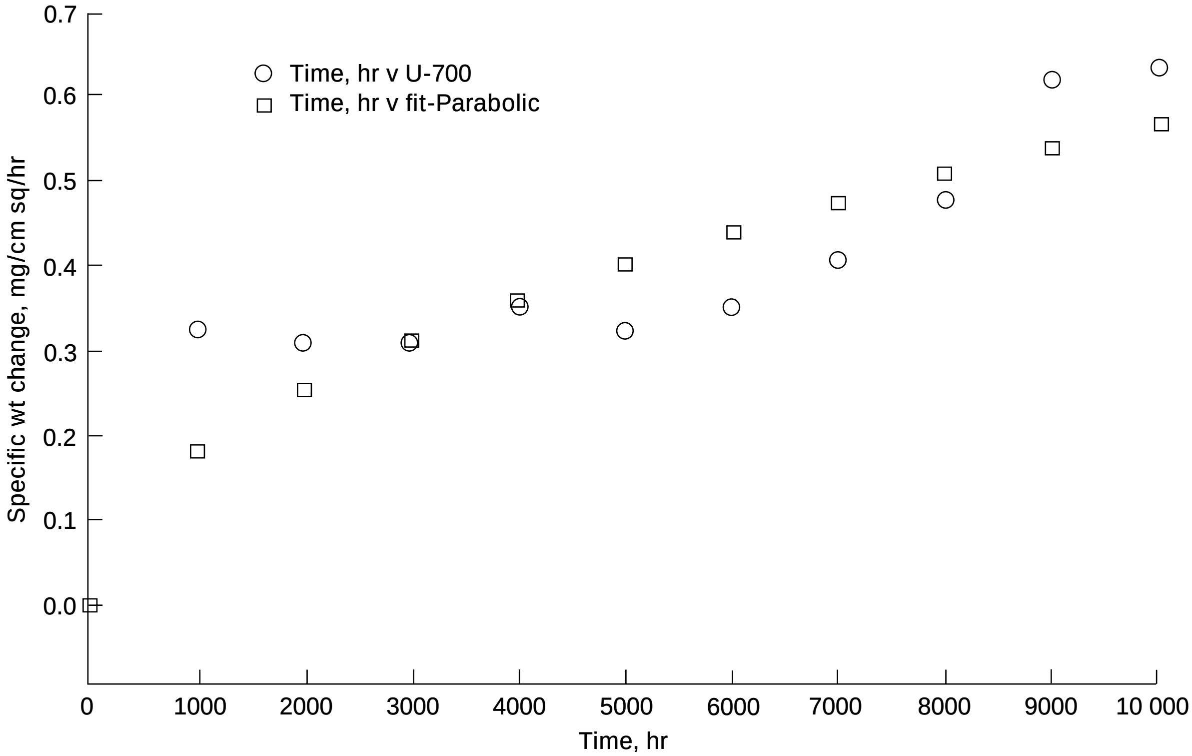

Figure 9.—Cyclic oxidation-1000 hr cycles in static air at 982 °C for a Ni-base alloy sample U-700.

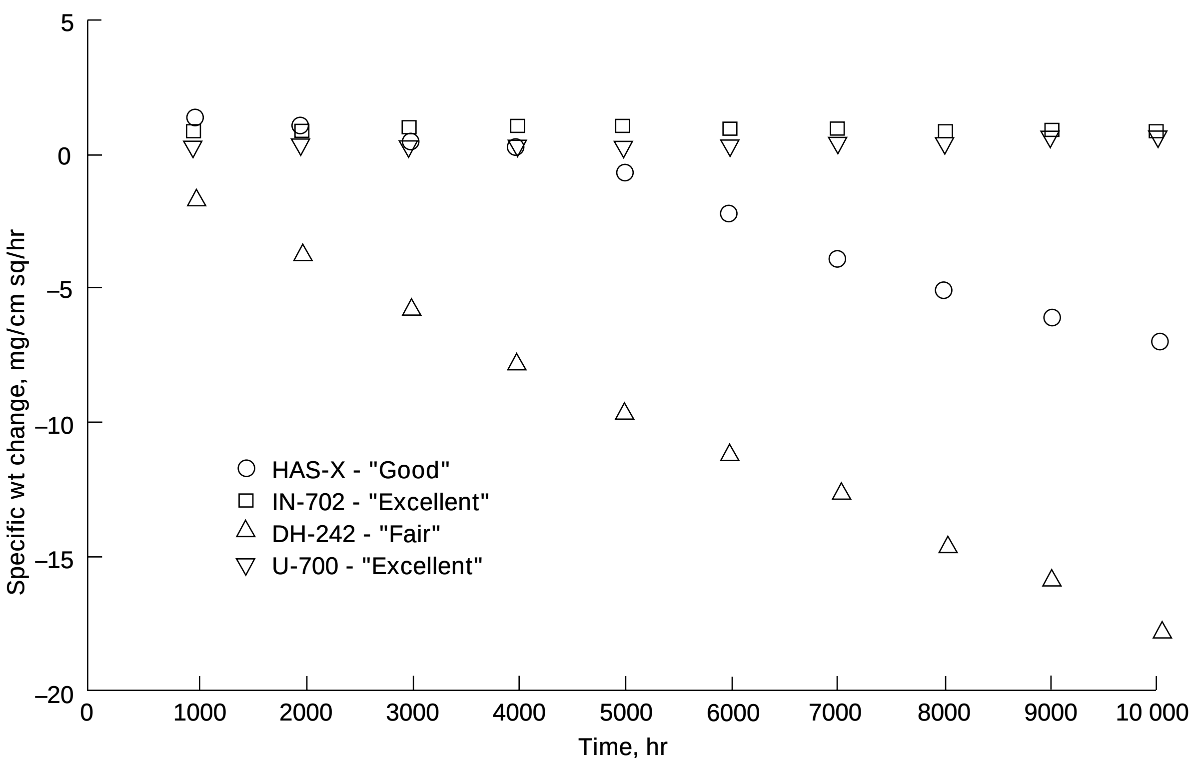

Figure 10.—Four typical oxidation plots showing "excellent" to "fair" behavior.

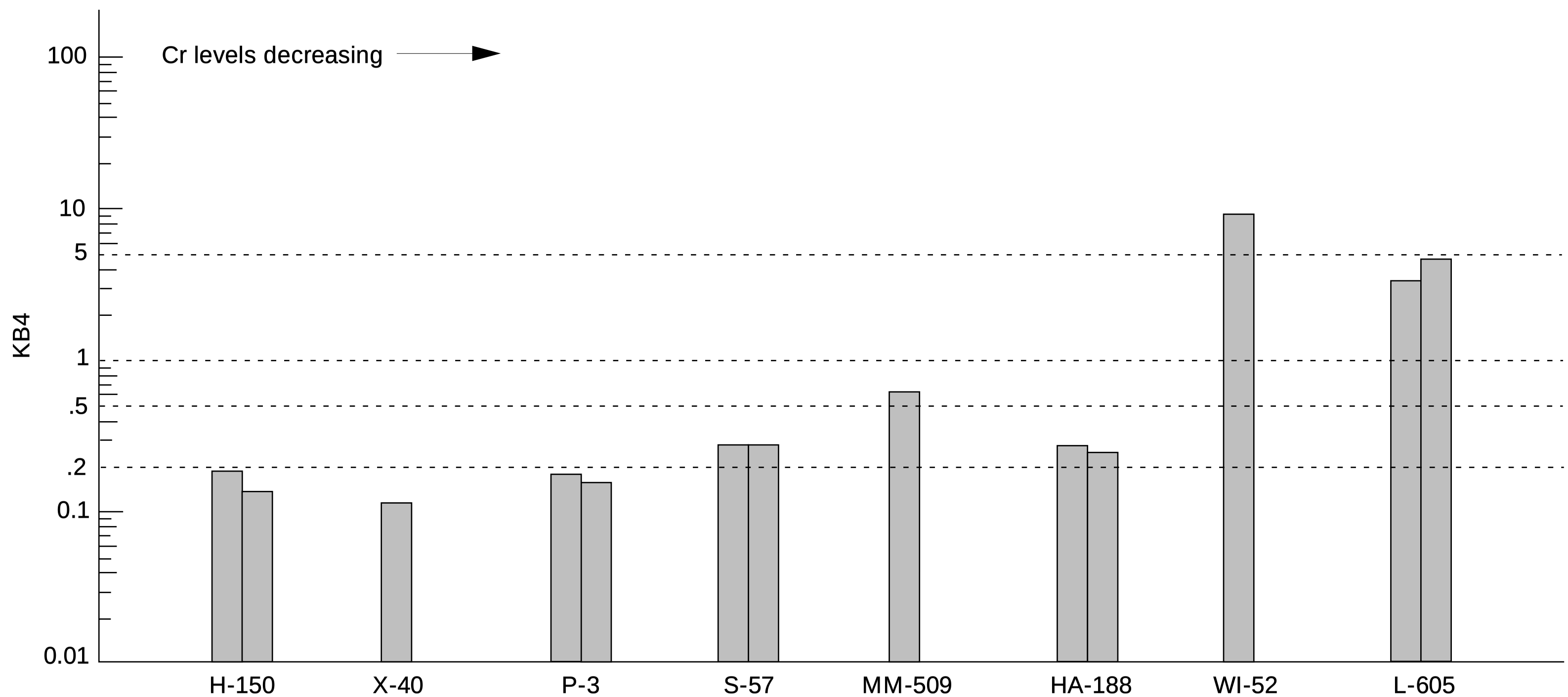

Figure 11.—KB4 ratings for chromia/chromite forming Co-base alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

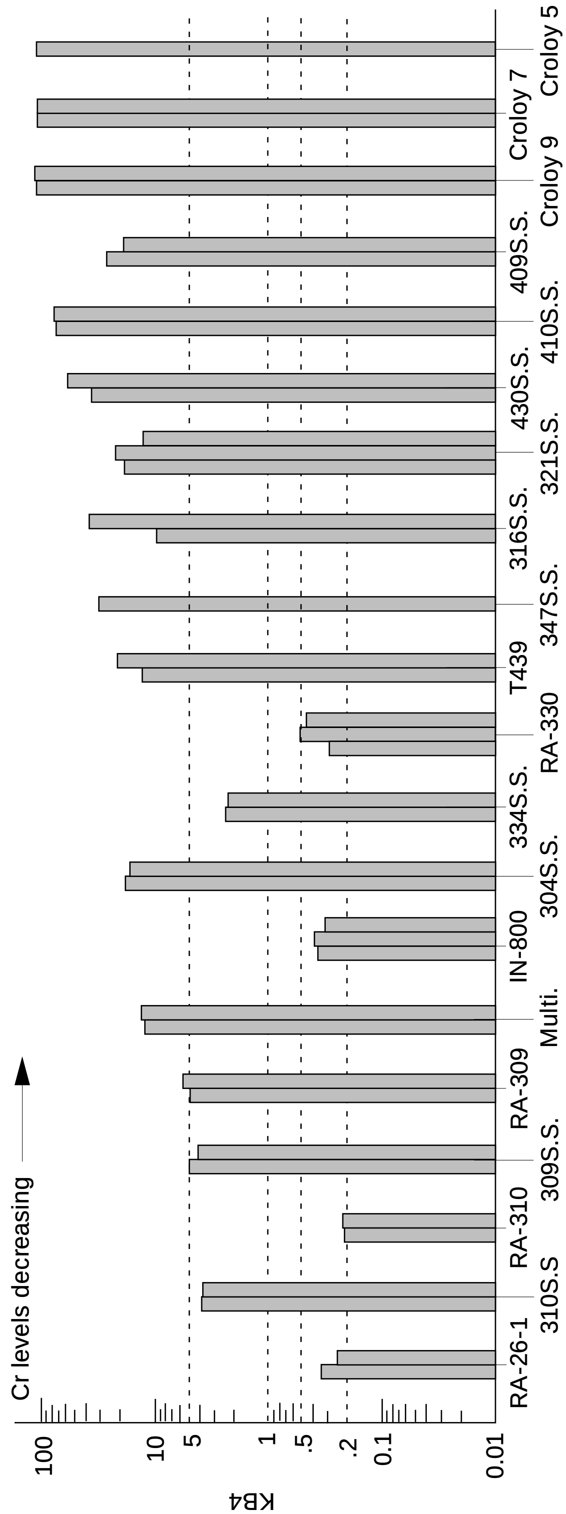

Figure 12.—KB4 ratings for chromia/chromite forming Fe-base alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

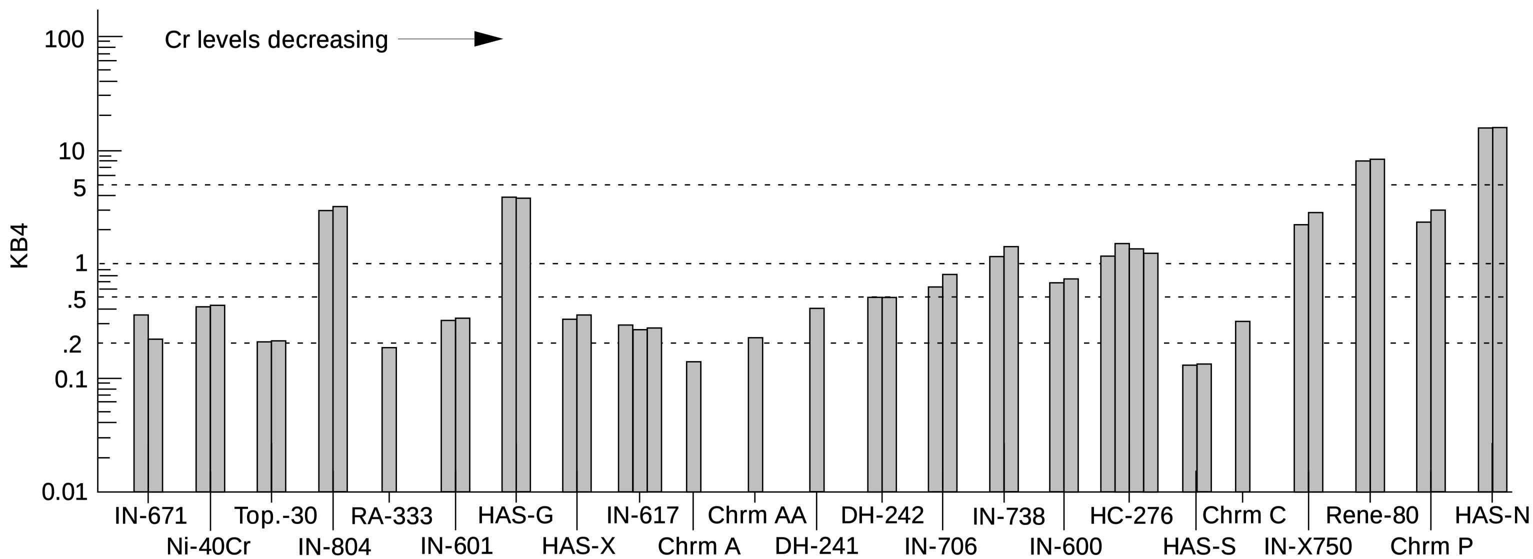

Figure 13.—KB4 ratings for chromia/chromite forming Ni-base alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

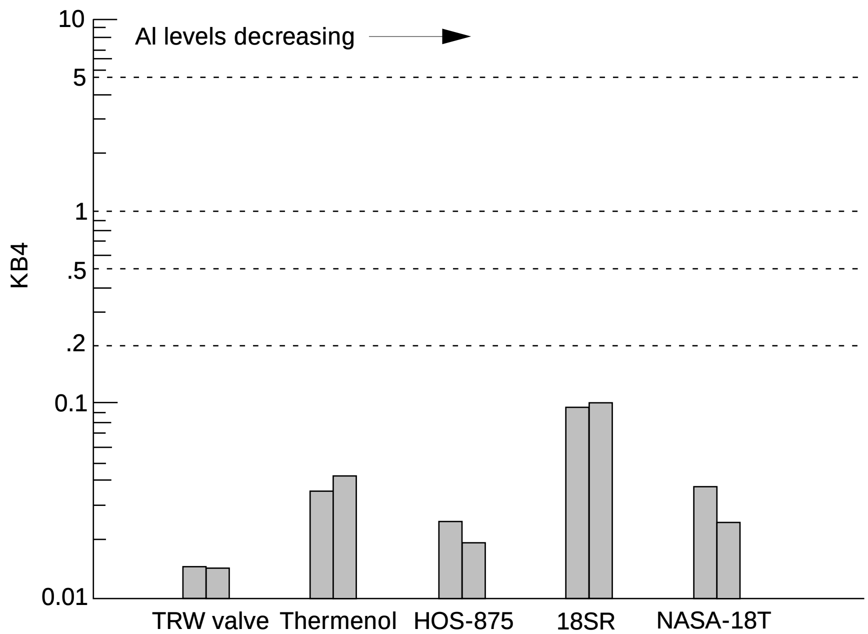

Figure 14.—KB4 ratings for alumina/aluminate forming Fe-base alloy (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

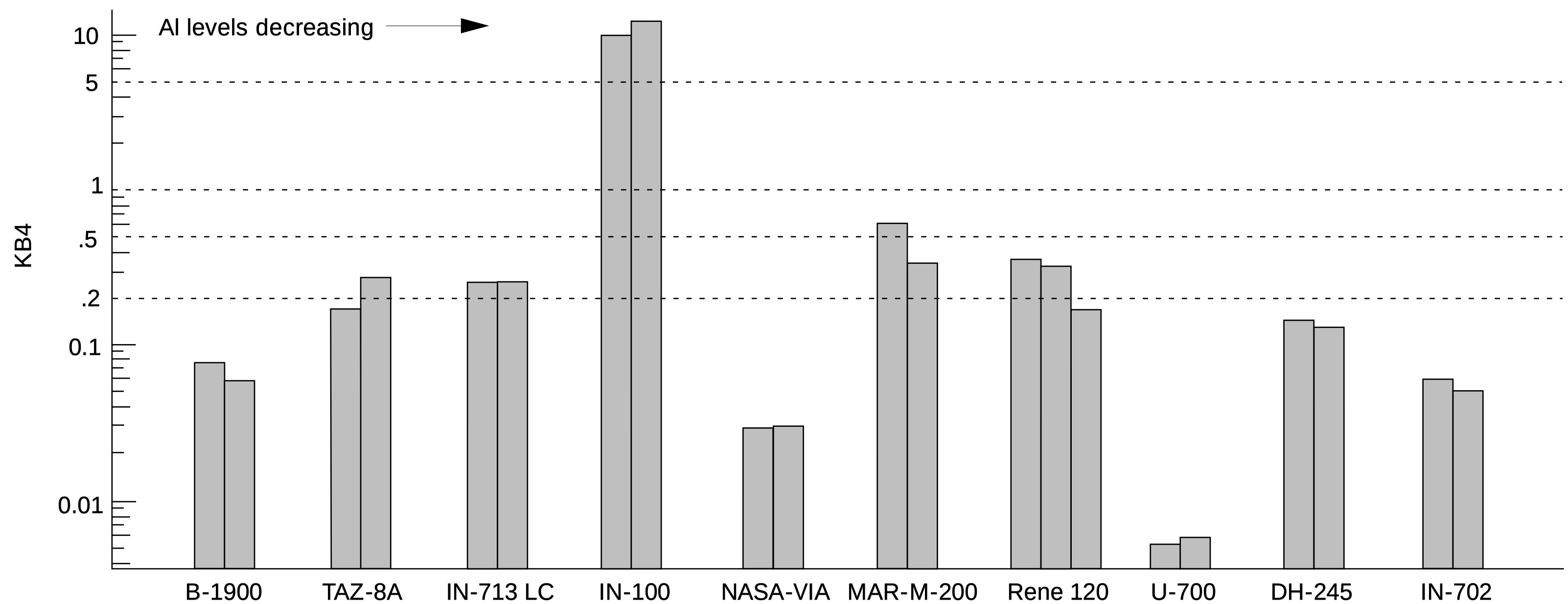

Figure 15.—KB4 ratings for alumina/aluminate forming Ni-base alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

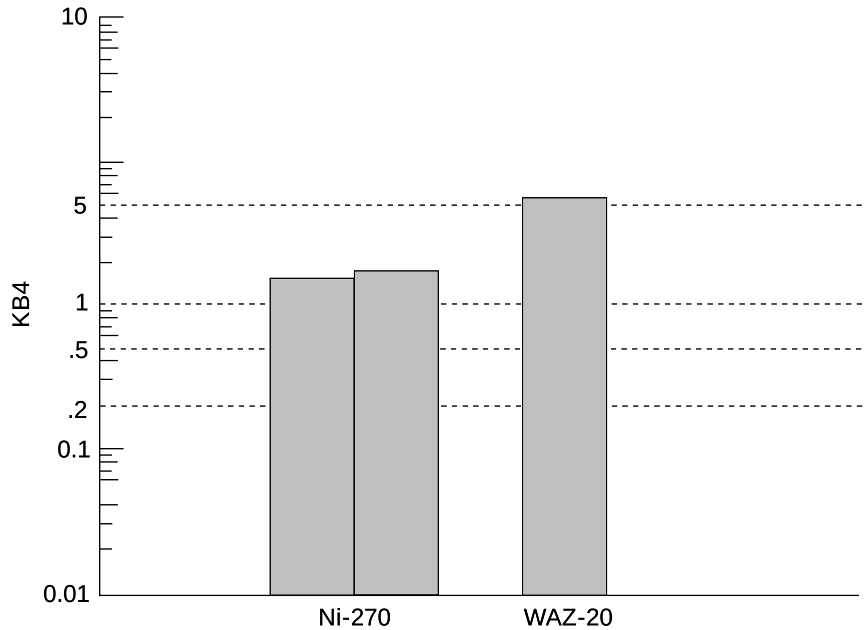

Figure 16.—KB4 ratings for nickel oxide forming Ni-base alloy (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

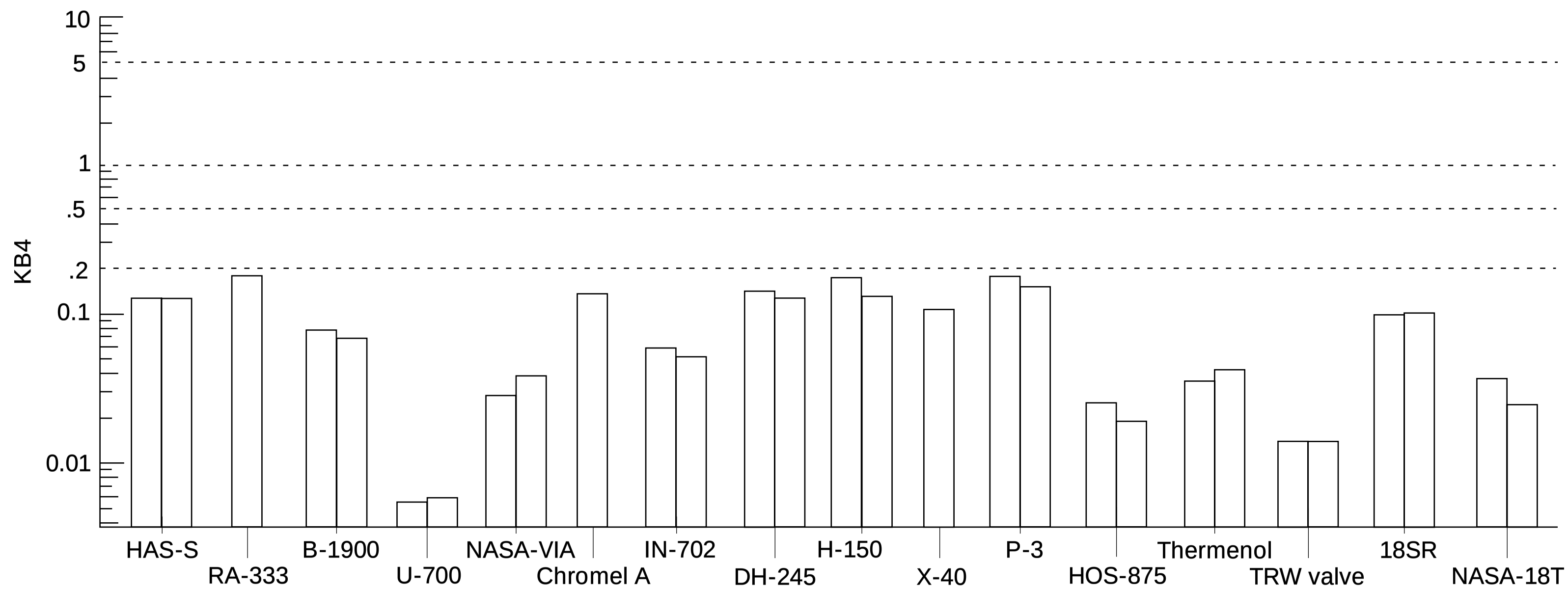

Figure 17.—KB4 ratings for the "excellent" ranked oxidation resistant alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic.

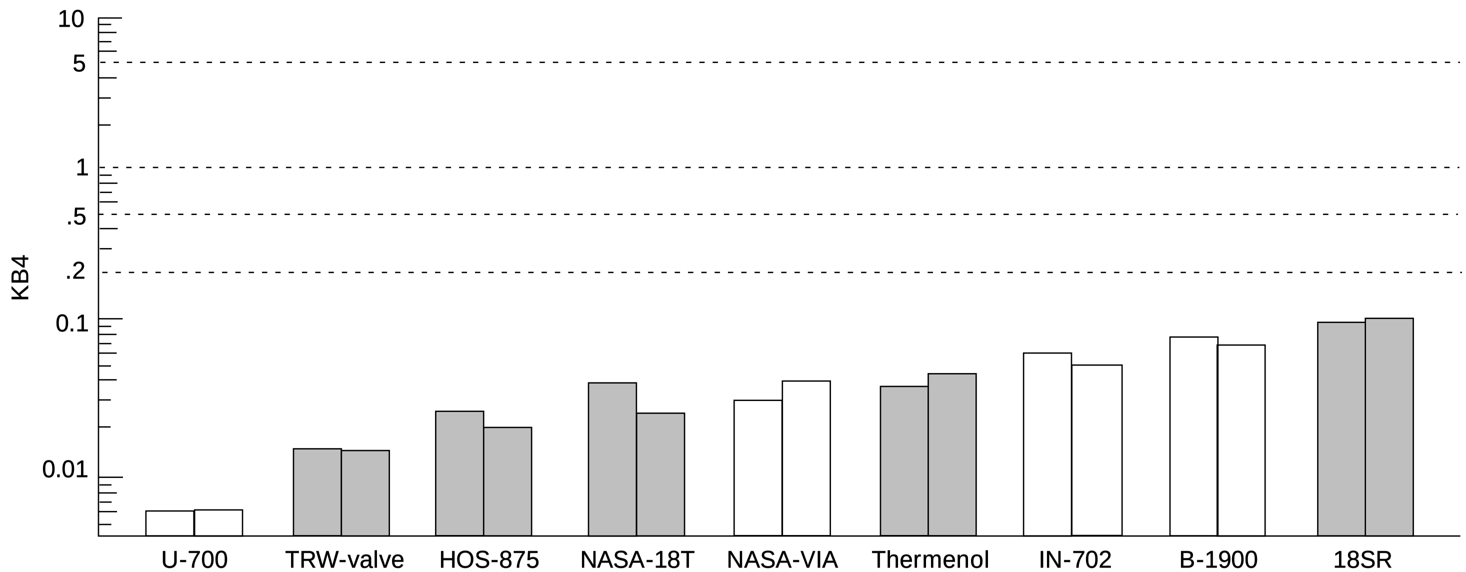

Figure 18.—KB4 ratings for the "best" of the "excellent" ranked oxidation resistant alloys (10-1000 hr cycles, 982 °C). KB4 rating: <0.2 excellent, 0.2 to 0.5 good, 0.5 to 1.0 fair, 1.0 to 5.0 poor, >5.0 catastrophic. Ni-base (open bars) and Fe-base (shaded bars).

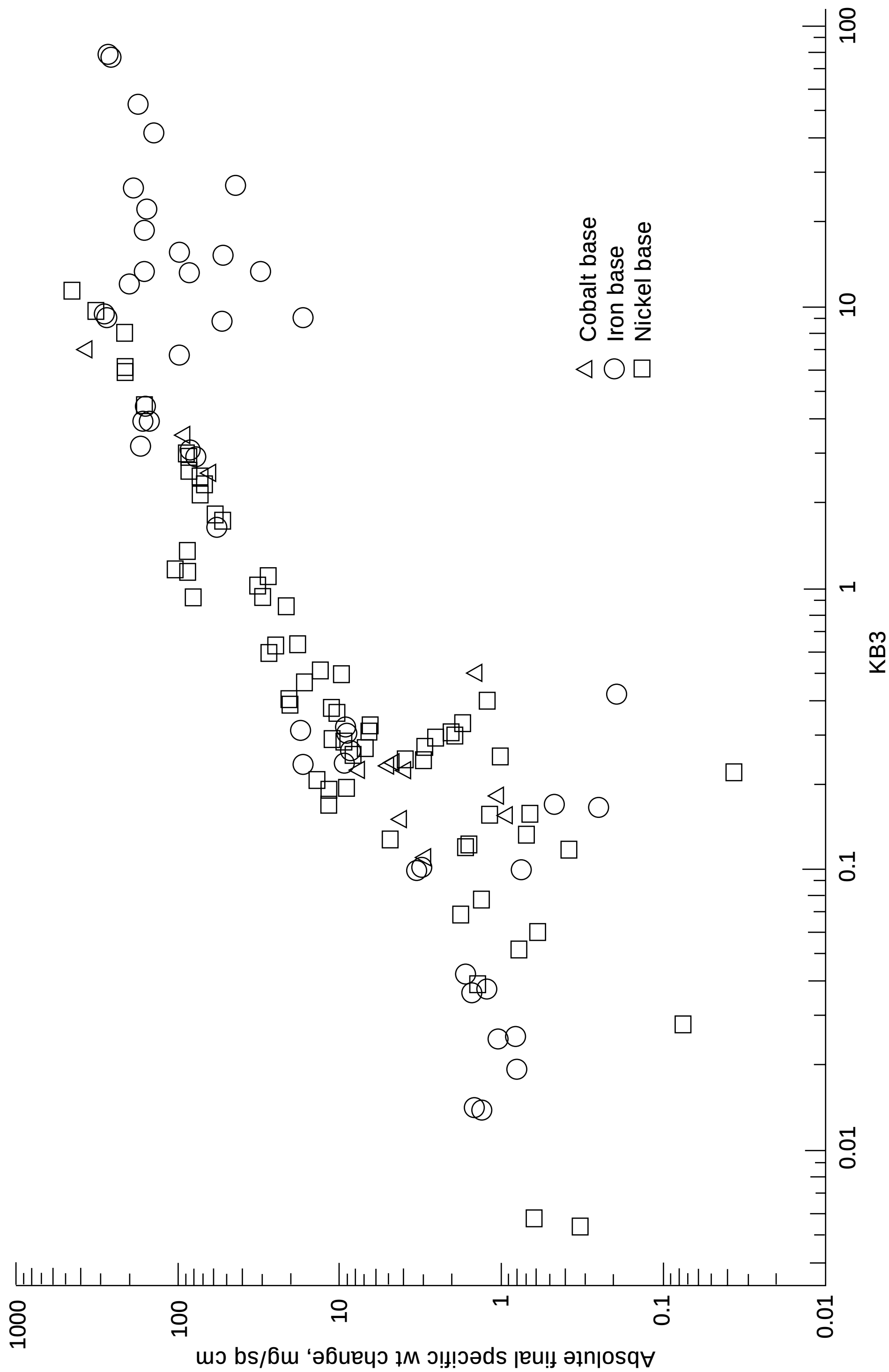

Figure A-1—Scatter diagram showing the relationship of the absolute value of final specific weight change to the oxidation attack parameter, KB3 (132 data points for 68 alloys).

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13. ABSTRACT ***(Maximum 200 words)***

Sixty-eight high temperature Co-, Fe-, and Ni-base alloys were tested for 10-one thousand hour cycles in static air at 982 °C (1800 °F). The oxidation behavior of the test samples was evaluated by specific weight change/time data, x-ray diffraction of the post-test samples, and their final appearance. The gravimetric and appearance data were combined into a single modified oxidation parameter, KB4 to rank the cyclic oxidation resistance from excellent to catastrophic. The alloys showing the "best" resistance with no significant oxidation attack were the alumina/aluminate spinel forming Ni-base turbine alloys: U-700, NASA-VIA and B-1900; the Fe-base ferritic alloys with Al: TRW-Valve, HOS-875, NASA-18T, Thermenol and 18SR; and the Ni-base superalloy: IN-702.

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